В. П. Карцев

МАГНИТ ЗА ТРИ ТЫСЯЧЕЛЕТИЯ

«Атомиздат»
Москва

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THREE THOUSAND YEARS OF MAGNETS

Translated from the Russian by Ann Feltham

Mir Publishers
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to the reader

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PREFACE

The universe is magnetic, from its vast, distant nebulae right down to elementary particles, and man is permeated through and through with myriads of magnetic fields from all sorts of sources.

We now take the magnet for granted and have a rather supercilious attitude toward it as an old-fashioned part of school physics lessons, with no idea, at times, of the number of magnets around us. I counted up one day; in my flat there are dozens—in my electric razor, in the radio loudspeaker, in the tape-recorder, and in a jar of nails. And I myself am a magnet; the biological currents in me give rise to a fantastic pattern of magnetic lines of force. Our Earth, too, is a gigantic blue magnet; and the Sun, a great, yellow sphere of plasma, is an even more powerful one. Galaxies and nebulae hardly visible even by means of radio telescopes are magnets of unfathomable size.

Nobody has ever been able to say (and probably never will): 'I know everything there is to know about magnets.' The question 'Why does a magnet attract?' will always fill us with a sense of Nature's inexhaustible variety and encourage to thirst after new knowledge and new discoveries. And, because of the immensity of the problem of magnets, this book will not provide a complete answer either.

Nevertheless we do know a great deal about magnets—in any event enough to exploit their power to our own advantage.

New materials, new magnets, amazing new equipment, and the most complex and sophisticated machines all became possible when scientists began to understand the mysterious manifestations of magnetism. The magnet, it seems, which not so long ago was incomprehensible and uncontrollable, is beginning without demur to obey the orders of man, who is penetrating its secrets. And here we would do well to recall the words of the poet Velimir Khlebnikov: 'No one could fulfil an order more exactly than the Sun if he were told to rise in the morning in the east.'

MAGNETISM IN NATURE

Interstellar Wanderers

Wherein we present information on theories of cosmogony, an essential of which is the presence in galaxies of a magnetic field.

In a pine forest not far from Serpukhov, a town near Moscow, there is a clearing with a rather strange shape. Viewed from the air it looks like a colossal circular embankment. Under the bank lie huge concrete slabs, forming a corridor that stretches for a kilometre and a half around the circle. In the corridor is housed a synchrophasotron, one of the largest particle accelerators.

Around the synchrophasotron a science city has grown up, where scholars from the Soviet Union, the People's Democracies, and France work.

Scientists come to Serpukhov in order to work on the accelerator there, which can impart the collossal energy of 76 thousand million electron volts (76 Gev) to protons.

And yet the Earth is constantly bombarded on all sides by the particles of cosmic rays from the secret depths of outer space, many of which have an energy thousands of millions of times greater than that obtained in the Serpukhov accelerator.

V. L. Ginsburg, Member of the USSR Academy of Sciences, thinks that cosmic particles achieve these inconceivable energies in gigantic interstellar accelerators. The essence of his theory is that in the vast expanses of our

Galaxy, in other distant worlds and in intergalactic space, there are magnetic fields in which particles can gather speed as if in an enormous natural cyclotron.

The sources of cosmic rays may be ordinary stars (like our Sun, for example), magnetic stars that can produce cosmic rays of much greater intensity than the Sun, and supernovae, and also, possibly, novae stars, which, we know, not infrequently appear.

Scientists were helped to this conclusion, in particular, by Chinese chronicles, in which, for thousands of years, the chroniclers had methodically and scrupulously noted down everything thought worthy of posterity's attention. Thus a chronicler who lived more than five hundred years ago described how a star had suddenly flared up in the sky, shining almost as brightly as the Sun. It was the first written record of a supernova ever made. Since then observation has established that such flares occur comparatively frequently—about once in 50 to 100 years.

How can the great brightness of supernovae, which lasts for a comparatively short period, be explained? According to the most commonly accepted of today's theories the cloud of gas and interstellar dust from which a star is subsequently formed possesses a certain rudimentary magnetic field, not very strong, possibly some thousandths of a gauss*. The lines of force of this field are very far apart (and the density of magnetic lines of force is usually taken to reflect the strength of a magnetic field). Through the force of gravity the cloud, which is made up of separate specks of dust and atoms of gas, begins to contract toward its centre. And the atoms and dust, in moving toward the centre, 'pull' the lines of force of the magnetic field with them.

* The gauss is the unit of induction in a magnetic field in the C.G.S. system. In a vacuum it is numerically equal to the strength of the magnetic field (see p. 17).

In this way gravitation causes the lines of force of the cloud's magnetic field to draw closer together and so increases their density and consequently the strength of the field. The cloud contracts faster and faster, a corollary of Newton's law of gravitation that the closer particles of matter are to one another, the more strongly they attract one another. Something like a chain reaction takes place. As the cloud contracts, the lines of force of its magnetic field also contract faster and faster. When the cloud approaches the size of a sphere with the 'critical gravitational radius', the induction of its magnetic field is already several thousand million gauss. Fast electrons coming into this field are sharply braked, giving off enormous quantities of radio waves and visible light. And that is possibly when supernovae shine so brightly.

A discovery made at the turn of the century by the Dutch physicist, Pieter Zeeman, helped to confirm this hypothesis. While investigating the radiation spectra of various substances he noticed something unusual: as soon as the investigated substance was put into a magnetic field the lines of the spectrum began to split up (Fig. 1). And the stronger the magnetic field around the substance, the more the lines, in consequence, break up. Therefore, if division of the lines is noted in the spectrum of a particular object, we can confidently assume that the object is in a magnetic field and we can judge the strength of the field by measuring the degree of division.

Using this method to investigate the spectra of several stars, Hiltner, the American astronomer, noticed that the light from stars was sometimes strongly polarized when it reached the Earth, as if a polarization filter, like that used by photographers to get rid of unwanted highlights, had been put in its path. In addition it was observed that the blue end of the spectrum of stellar light had been totally filtered out, which is normally a sure sign that the light has passed through interstellar dust and gas clouds.

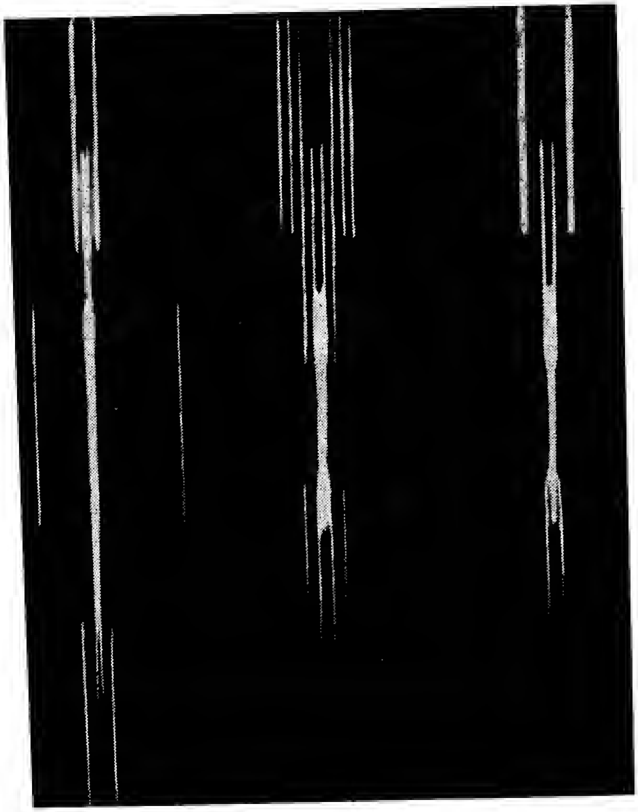

Fig. 1. The effect of a magnetic field on the emission spectrum of a substance: the stronger the field the more the spectral lines are divided.

Putting these two aspects of stellar radiation together, scientists concluded that the polarization was not a result of the properties of the star itself but had occurred during the ray's long journey across the expanses of the Galaxy.

What causes the polarization? We can explain it if we assume that interstellar space is filled with particles that are not spherical, but have been stretched in one direction or another by the galactic magnetic field.

Having measured the displacement of the spectral lines astronomers calculated that the magnetic field was several millionths of a gauss. That, it would seem, is insignificant; but it is difficult to imagine the immense role that a magnetic field, even one as weak as this, apparently plays in the structure of galaxies.

How do galaxies manage to preserve their shape over thousands of millions of years?

Why do the gigantic gravitational forces, acting over such a long period of time, not crush the galaxies and drive them all to a single centre, and lead to gravitational collapse, which would be the logical result of the process?

The magnetic field of the galaxies, as the German astrophysicists Shluter and Lust have shown, hinders these processes. Furthermore it is because of magnetic forces that our Galaxy is able to revolve as a single whole without disintegrating (during its existence it has completed more than fifty revolutions). Figuratively speaking, the magnetic field is the stable framework that protects galaxies against the destructive action of gravitational forces.

Certain other characteristics of nebulae, for example their spiral and fibrous structure, can also be explained by the presence of a magnetic field.

The gas of luminous nebulae, electrically charged (i.e. electrified by stellar radiation), moves along the lines of force of the magnetic field. As a consequence the structure of the nebulae frequently resembles the pattern usually obtained when iron filings are tapped on a piece of paper above the poles of a magnet.

The similarity of the shape of galaxies to this pattern was convincingly demonstrated by the veteran Soviet astronomer, Professor B. A. Vorontsov-Velyaminov. He

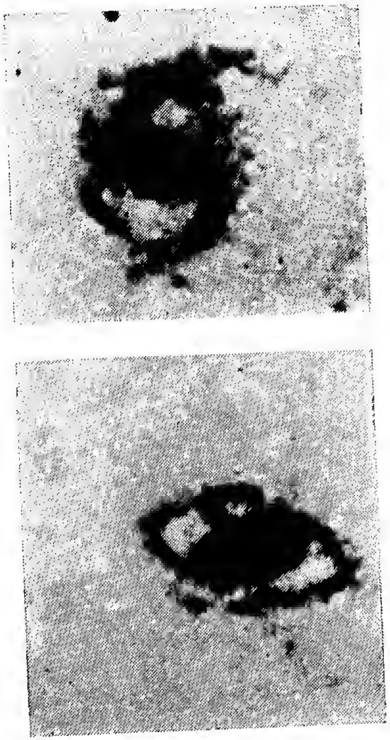

Fig. 2. The shape of some galaxies resembles that of the lines of force of a bar magnet.

made a unique 'collection' of galaxies, both single and interacting, and compared them with the field patterns of a uniformly magnetized sphere or bar and of interacting magnets. They were almost completely identical. In several cases it was clearly visible how the gas, moving along the lines of force, flowed from one pole of the galaxy to the other. Calculations convincingly demonstrated that the magnetic field earlier measured in our Galaxy was quite

sufficient to preserve the latter's shape for thousands of millions of years.

The magnetic fields in galactic space, however, are not exclusively weak. In investigating the radiation of several stars physicists concluded, from analysis of the splitting of spectral lines, that they had very strong fields. A field of 34 400 gauss has been measured on a star (to an accuracy within 300 gauss). Strong magnetic fields have also been measured on giant stars with diameters a hundred times that of the Sun and were found to be around 1000 gauss.

Magnetic fields have now been noted on a hundred stars. Astronomers think that the induction of the magnetic field at certain latitudes on some of them is between 50 000 and 100 000 gauss. If this proves the case, scientists will succeed in clarifying many of the ambiguities in theories of the generation of cosmic rays and radio waves in the Sun and stars.

But what gives rise to the magnetic fields of stars?

The English physicist P.M.S. Blackett, F.R.S., tried to answer that.

Secrets of the Gold Cylinder

Wherein we tell of the intuition against which the gold cylinder rebelled, thereby undermining one of the most beautiful theories of the origin of the magnetic fields of the Sun and stars.

Blackett's train of thought was rather curious. After analysing a great many physical formulae he came to the conclusion that the most fundamental laws in physics could be stated quite simply (we need only recall Einstein's very simple expression of the relationship between mass

and energy—$E = mc^2$). Paul Dirac, who had also noticed this, said that any physical theory should be mathematically elegant. In addition many formulae from apparently different fields of physics are often written in a very similar way (recall, for instance, the law of universal gravitation and Coulomb's law). From considerations like these Blackett wrote a simple, mathematically very pleasing equation, which in his opinion linked the magnetic field with the motion of a body. Any body with translational or rotational motion, he suggested, created a magnetic field around itself.

To check his hypothesis a massive cylinder of twenty kilograms was made from pure gold and was taken out into the country in order to get away from the 'background' of industrial magnetic fields. There it was rotated at high speed, but the experimenters failed to establish any noticeable connection between its mechanical and magnetic moments. The formula that had looked so pleasing when written down was unfortunately not verified by the experimental results.

But Blackett must be given his due: he was not one to be embarrassed by the results of experiments on a small gold cylinder. He had his sights set on the planets and the stars.

Here, indeed, he does find some support, first and foremost from the Earth, Jupiter, the Sun, and the star White Dwarf E 78 in the constellation Virgo. In all these heavenly bodies the relationship of the angular momentum and magnetic moment is identical and approximately of the order that Blackett predicted.

There are, however, stars whose magnetic fields are known for certain to be constantly changing and whose sign sometimes even alters. In order to present a balanced picture Blackett was forced to admit that the mechanical moment of a star also changes sign, which meant that from time to time a star would begin to rotate in the opposite

direction. Although there are bound to be many more secrets and surprises in the depths of the universe, that would not only astound the ordinary man but lead any researcher up the garden path, scientists nevertheless regard such a possibility with scepticism.

Only further research will show whether or not Blackett was right.

The strange character of the Sun's magnetic field has given rise to doubts about his theory.

The Sun's magnetic field was first detected more than half a century ago, using Zeeman's technique, which we mentioned above. The measurements showed that it was very similar to the Earth's, with poles, magnetic meridians, and a magnetic equator. Its strength is approximately 50-100 times greater than the Earth's and averages 25 to 50 oersteds.*

Further research, however, yielded completely unexpected results. Instead of a strict pattern of lines of force repeating the field of a uniformly magnetized sphere, researchers saw a disorderly conglomeration of variously magnetized regions.

The strength of the magnetic field fell sharply and proved to be only one or two oersteds. On the other hand, the field in sun spots is immensely strong, 3000 oersteds and more. Two neighbouring spots, normally joined by an enormous fiery flare, must necessarily be of opposing polarity—if the magnetization of one was north that of the other must be south. From study of the shape of the flares solar physicists concluded that they exactly repeated the pattern of the lines of force of a horseshoe magnet. It has now been reliably established that super-hot gas flows out from the spots along these lines of force (the gas is charged and con-

* The oersted is the unit of magnetic field strength in the C.G.S. system. The strength of the Earth's magnetic field is approximately 0.5 oersted.

sequently cannot move across them; for only when charged particles move along the lines of force are they unaffected by magnetic forces).

In the solar system it has been found that the magnetic field of Jupiter, which is as high as 50 to 100 gauss, is the strongest.

Signs of a very strong field have also been noted on Io, one of Jupiter's satellites. And a sizeable field has been detected on Mercury. The American interplanetary station Mariner-10, which flew past Mercury, 'reported' back to Earth that Mercury's magnetic field is a hundred times weaker than that of the Earth. It is not excluded that Mars has a weak dipole field. The Apollo-16 astronauts Young and Duke and the Soviet Lunokhod-2 both observed a weak magnetic field on the Moon.

A group of Soviet scientists sought to explain the role of the Earth's magnetic field. From analysis of the parameters of its rotation they concluded that the rotation is caused by the magnetic field.

From this theory it follows logically that we are indebted to the Earth's magnetic field for day and night and the four seasons, and therefore for nothing more nor less than life itself.

Apart from the cosmic rays that bombard our Earth, the Sun sends out streams of charged particles, many of which have an energy greater than 100 million electron volts (100 MeV).

During the Sun's chromospheric flares, for example, protons with an energy above 100 MeV are generated in vast numbers. In years of heightened solar activity (the cycle of the Sun's activity is eleven years) more than 3000 flares are observed, of which 15 per cent are major ones. It is now thought that during each flare the Sun ejects streams of plasma in one particular direction. Approximately 4 per cent of them reach the Earth. In addition to the ordinary flares large relativistic flares occur once every three months,

discharging powerful currents of protons with an energy of several giga-electron volts.

The density of particles in the Earth's orbit is approximately 10^8 particles per cubic centimetre. Most of them never reach the Earth's surface, as they are screened by the magnetic field. Any charged particle entering this field has its trajectory bent, is pulled onto the lines of force, and consequently begins to orbit around the Earth, so that only an insignificant fraction reach the surface.

If the Earth did not have a relatively strong magnetic field it would long since have been turned into a desert scorched by cosmic rays and be as lifeless as the Moon.

People only became aware of the existence of the Earth's magnetic field comparatively recently, some three hundred years ago, although they had been unknowingly exploiting it for thousands of years before that.

* * *

Caravans tread the boundless sands of the Gobi Desert. To right and left, as far as the eye can see, are cheerless yellow dunes. The sun is shrouded by yellow dust. It is a long way from the imperial pagodas on the banks of the Yangtze to the minarets of the kingdoms of the Kushans. The caravaneer would be hard pressed had he no white camel in his train—a white camel with its precious load, priceless although not gold, or pearls, or ivory. Lying between the camel's humps and protected by a carved wooden box is a clay pot of water in which floats a cork with an oblong piece of magnetized iron. The edges of the pot are painted in four colours—red for south, black for north, green for east, and white for west. The pot and its bit of iron are a primitive compass showing the caravaneer the way across the endless sands.

In Chinese chronicles we also find descriptions of magnetic gates through which an armed ill-wisher was unable to pass, of magnetic roadways, and of other applications

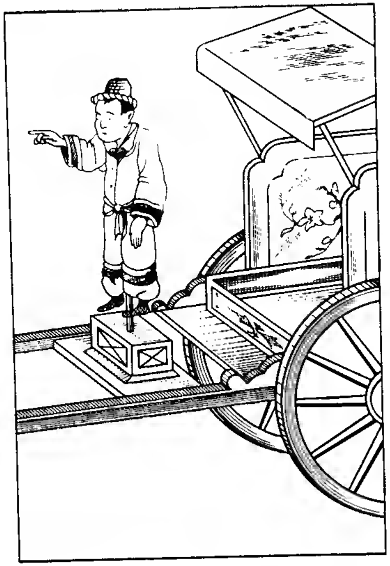

Fig. 3. One of the first compasses, built thousands of years ago. The arm of the figurine fixed onto the carriage always points south.

of the magic stone *chu-shih*, which was simply magnetic iron ore.

One Chinese legend tells of the victory of the Emperor Huang-ti nearly five thousand years ago, which he owed to his craftsmen. They had made a chariot on which they fixed the figurine of a man with its arm outstretched. The figurine swivelled round so that the arm always pointed south (Fig. 3). With this chariot Huang-ti's troops were able to attack the enemies from the rear in a thick mist and defeat them. If we abandon legend for firmly established facts, the compass becomes much 'younger'. In old Chinese encyclopaedias there is information that the magnetic needle was used on ships in 400 B.C. In a museum collection there is a Chinese compass a 'mere' thousand years old resembling in shape a traditional Russian (Khokhlo-

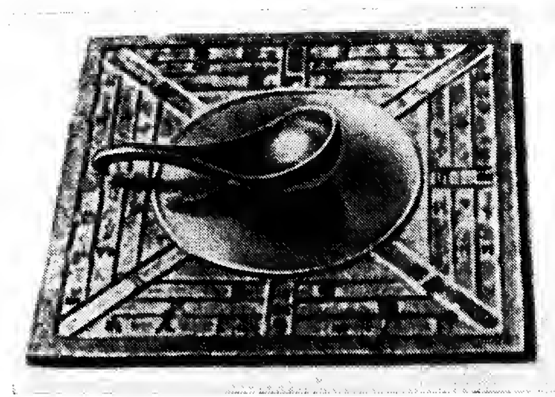

Fig. 4. Chinese spoon-like compass.

ma) painted wooden spoon.

In Europe, too, the Earth's magnetism was apparently long exploited for orientation, employing a lodestone suspended from a thread or fixed to a small piece of wood floating on still water. In an early French novel a magnet was described as a 'marinette' from which we may conclude that magnets were used at sea.

From the beginning of the eleventh century all discoveries concerning the magnet and compass of any value were made in Europe. Thus scholars think that the inhabitants of the Italian coastal town of Amalfi (some even say the jeweller Flavio Gioia) may first, some six hundred years ago, have made the compass as we know it today, when they furnished it with a rotating disc marked out in divisions. All the great geographical discoveries were made with the aid of such a compass.

Magnetic variation or deviation, by which we mean the angle between the geographic and magnetic meridians,

was also known quite long ago. On 13 September 1492 Christopher Columbus wrote in his log that before nightfall the compass showed a declination toward the northwest, but that by morning this variation was less marked. It made Columbus's superstitious sailors panic because they were well aware that the needle should by rights be slightly displaced toward the east. They became mutinous. Unbeknown to the sailors Columbus moved the compass card so that it once more showed the 'normal' deviation. And to make everything seem all right, and so as not to contradict the astronomical observations, he was forced to declare that the compass had not changed its direction, but that the Pole Star had moved from its accustomed place. The change in the magnitude and sign of the variation of the magnetic needle on any parallel of latitude is now a well-known phenomenon and is widely employed in determining ships' positions.

True, not by everyone. In Rockwell Kent's book *N by E*, for example, we find the following conversation between the author and the mate of a fishing vessel:

'"When I say North," said the mate, "I mean where the compass points."

'"When I say North," I answered, "I mean North."

'At the end of three quarters of an hour it was terrific.'

After Columbus's time many scientists painstakingly studied the Earth's magnetic field and magnetic deviation, but it was only in 1600 that an explanation of why the compass needle was attracted toward the Earth's poles was given, when William Gilbert, court physician to Queen Elizabeth I, published his famous treatise on magnetism *De Magnete magneticisque corporibus, et de magno magnete tellure*.

In this book Gilbert convincingly demonstrated with an enormous amount of experimental material, that the magnetic field of the Earth is like the field of a uniformly magnetized sphere made of magnetic iron ore. In explaining terrestrial magnetism Gilbert suggested that the Earth was made of magnetized iron, which created the magnetic field; but his proposition was not correct. He himself discovered that iron, at the high temperatures that we now know to exist at the centre of the Earth, completely loses its magnetic qualities.

Gilbert's book laid the foundations for the scientific approach to magnetic phenomena in general and to terrestrial magnetism in particular. 'For nearly two centuries,' Prof. A. N. Krylov, Member of the Russian Academy of Sciences, wrote about his work in 1920, 'nothing of substance that was not in Gilbert's book, or was not either a repetition or a development of what he had already done, was added to the subject.'

Magnetic observatories, voyages by demagnetized ships, the dramatic adventures of Sir James Ross on his expeditions to the North and South magnetic poles, the Arctic drift of the Papaninites (I. D. Papanin, E. E. Fedorov, P. P. Shirshov, and E. T. Krenkel), and the launching of geophysical rockets and artificial earth satellites—have all been directed to furthering the study of terrestrial magnetism. And we can say with confidence that the magnetic maps of our planet have been drawn with no less accuracy than the geographical ones.

Earth—The Blue Magnet

Wherein we touch on the possible causes of terrestrial magnetism and introduce the reader to the 'pra-field' and the strange idea that the Earth is nothing more nor less than a gigantic electric machine.

But the main problem—what causes terrestrial magnetism—has still not been solved. Gilbert's hypothesis, as we

Fig. 5. Gilbert's figure of a smith at his anvil, illustrating his discovery that a piece of red-hot iron struck by a hammer in the north-south position (*septentrio-auster*) becomes magnetic (From the *De Magnete*).

have seen, did not hold water, and for that matter neither have many other more modern theories.

The most popular theory today is probably that of the 'self-exciting dynamo'.

This theory has been proposed in various guises and at various times by a number of eminent physicists, among whom we will single out J. I. Frenkel of the USSR, the American W. M. Elzasser, and the Englishman E. C. Bullard.

The theory is founded on the discovery made a century and a half ago by the Danish scientist Hans Christian Oersted that there is a magnetic field around every conductor carrying electricity. In order to explain terrestrial magnetism along these lines one must assume that an electric current of some sort circulates in the depths of the Earth. In principle that is not impossible since it has been demonstrated that the planet has a liquid conductive core,

through which electricity could freely flow. The problem is—where could the current arise?

This is where the 'dynamo' theory comes in. In the Earth's metallic, liquid core conditions may be created by temperature variations at different points that could give rise to convective currents in the conductive material. If the motion should occur in even a very weak magnetic field an electric current would be generated capable of giving rise to a relatively strong terrestrial magnetic field. Exactly where the primordial, albeit weak, magnetic field comes from is still not quite clear. It may be that it is left over from the earliest periods in the evolution of our galactic system; for that is not impossible since the colossal size of these heavenly bodies (and consequently their low electrical resistivity) would have led to extremely long periods when the electric currents and the magnetic fields were attenuated.

Many of the magnetic fields recorded by astronomers' radiotelescopes are thousands of millions of years old. It is possible that the Earth's 'pra-field', giving rise to the field in which we find ourselves, is the remains of some remote cosmic catastrophe.

Magnetic fields are also a characteristic of individual atoms, nuclei, and electrons. Scientists suggest that there are magnetic fields of millions of gauss deep within atoms.

Living nature, too, has its magnetic fields. It has been convincingly shown that biocurrents exist in animals and vegetative currents in plants. And if you consider that a current inevitably sets up a magnetic field around it, obviously every human, and every tree, and even the minutest living organisms, have magnetic fields, though not very large. When a person flexes his muscles he sets up a magnetic field on the surface of his arm with an induction of one-hundred-thousandth of a gauss.

The presence of a magnetic field in the human heart was exploited, in particular, in the first magnetocardiographic

apparatus, made in Voronezh. By using this apparatus which recorded the slightest change in the heart's magnetic field, doctors were able to obtain essentially new information about the functioning of the heart and to make it easier to give an early diagnosis of such dangerous diseases as dystrophy of the myocardium and hypertrophy of the heart muscles. Magnetocardiographs have made it possible to discover heart defects that even the most sensitive electrocardiographs could not spot.

WHAT LIGHTNING HAD TO TELL US

The Discovery of Electromagnetism

Wherein we talk about the discovery of electromagnetism, which has been attributed to certain definite persons, although thousands, many of whom died long ago, were actually involved, to whom in the final analysis we owe the discovery of one of the fundamental laws of the universe, now expressed in the first of Maxwell's equations.

Among Leo Tolstoy's writings are some in a popular science vein. Here is what he had to say about electricity:

'After electricity had been thought of, it began to be applied practically: ways were invented of using it for gilding and silvering, for lighting and for transmitting signals over great distances. To do so pieces of different metals are put into small jars of liquid. Electricity accumulates in the jars and is led along a wire to any spot designed, and there another wire leads it into the earth.'

We must suppose that when he says 'after electricity had been thought of' he has comparatively recent times in mind—something in the region of 100 or 150 years before his own time or 150 to 200 years from the present.

Modern scholars have several reasons for believing that electricity was 'thought of' some three or four thousand years ago and that 'ways of using it for gilding and silvering' were invented at the same time. The evidence may lie in the strange objects found by archaeologists in the dried and hardened silt not far from the banks of the Tigris, south of Baghdad.

What are these 'strange' objects, and what is it that is strange about them? Mainly the fact that archaeologists could not understand their significance for a long time. These small vessels made of dried clay were filled with unusual objects, small, corroded copper cylinders and iron bars. After examining the cylinders archaeologists decided that the corrosion was most probably the effect of acetic or citric acid, both of which were well known at that time. But the most unexpected surprise came at the bottom of the vessels—a thin, unsightly layer of bitumen which even today is sometimes used as an insulator.

The minds of the scholars worked as follows: if copper and iron plates were put in a pot of acid, and separated by an insulator (bitumen), it would be nothing more nor less than the most ancient chemical source of current, the discovery of which we attribute to a man who lived some three thousand years later!

Some archaeologists think that the gold plating on Babylonian jewellery is so fine that it can only have been done galvanically (i.e. electrolytically).

The ancients may have known much more about electricity than we suspect.

* * *

The eminent Egyptologist Heinrich Karl Brugsch (Brugsch Pasha) established that the Egyptian temples had lightning conductors, in the shape of tall wooden masts with a metal sheath. The ancient Hindus also used similar poles, only made of iron.

The tall bronze Roman statues of the time of Numus Pompilius and Tullus Hostilius also served to avert the blows of Jove the Thunderer from the sinful heads of citizens.

In the reign of Charlemagne Roman peasants set up tall stakes in their fields to 'bend the thunder'. But we should note that the emperor himself strictly forbade the

erection of such stakes on the quite modern pretext of combating superstition.

Surely the electrical nature of lightning was as apparent to the ancients as it became comparatively recently to Benjamin Franklin?

It is generally accepted that man has known about electricity since the young daughter of Thales of Miletus, that outstanding observer and materialist philosopher, noticed, when trying to clean tiny specks of dust and thread from her amber spindle, that they quickly stuck to it again when wiped off.

The property of amber to attract bits of cloth, thread, and straw was apparently very well known before Thales, and not just in Miletus. This attraction probably explains the name for amber in various languages: *electron*, that which attracts to itself (Greek); *harpax*, the robber (Latin), *kavuba*, that which attracts chaff to itself (Arabic).

Amber and objects like it had yet another mysterious property: when rubbed in the dark amber gave off bluish sparks, which were accompanied by a slight crackling or almost inaudible rustle. The phenomenon was so feeble that it was almost unthinkable to identify it with the great flashing sword, the lightning and thunder that filled the ancients with terror and panic. It took thousands of years to bridge the gap between them so close in nature yet so different in scale.

Amazingly, it was not for nearly two thousand years after Thales that the mysterious properties of amber attracted the attention of William Gilbert of Colchester.

He was a man highly respected by his contemporaries. He was a confirmed investigator. All the time left to him after his 'main job' he devoted to experiments on electricity and magnetism. The very word 'electricity' was introduced by him.

The task he assumed, to put the host of known facts into logical categories, was enormous.

What exactly was the job Gilbert took on? What were the facts he had to analyse?

From the Middle Ages only certain fragments of true knowledge had come down to Gilbert, and they were in the weirdest combinations.

Mediaeval scholars thought that everything in the world was divisible into 'magnets' and 'feameds'. Magnets embraced all the objects that attracted each other: magnet and iron, amber and dust, the barnacle and the bottom of a ship, bees and flowers. Feameds included all things that exhibited an antipathy for each other: magnet and candle flame; the like poles of a magnet, and so on.

By going without entertainment and pleasures Gilbert paid out of his own pocket for the countless experiments that led him to several extremely important conclusions. One was that the attraction of amber and of a magnet is different in nature. In other words, he succeeded in separating magnetic and electrical phenomena into two classes, which from then on were investigated separately. And it took some time, nearly 200 years, and the efforts of many scientists before electricity and magnetism were once more united, this time on a new basis.

Gilbert also discovered quite a few substances which, like amber, were able to attract small pieces of material and specks of dust.

Anxious to find out more about these substances Otto von Guerike, the inquisitive burgomaster of Magdeburg, in Germany, made a strange machine, which consisted of a globe of sulphur rotated by a simple mechanism. A metal chain attached to a long metal beam suspended on ropes just touched the rotating sphere. When the sphere was held in the hands while turning it developed a sizeable electric charge which was led off to the beam by the chain. The machine could be used for electrical experiments.

The globe of sulphur was prepared as follows. A thin glass sphere was filled with molten sulphur. When the

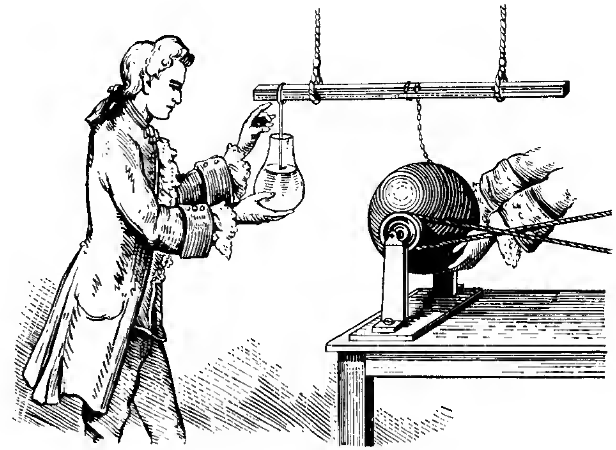

Fig. 6. Early experiments on electrostatic machines. 'These are terrifying experiments and I do not recommend anyone to repeat them', one of the first investigators wrote.

sulphur had cooled the glass was broken, leaving a sulphur ball. Unfortunately, von Guerike had too much respect for the scholars of his time to rotate a simple glass sphere. He required a *sulphur* ball like the one Gilbert had written about. Very little was known then about the electrical properties of glass. If the burgomaster had only tried rubbing his glass sphere with his hands he would have got a much more powerful machine.

The sulphur ball, however, enabled him to do some very effective experiments: when the globe was excited by the friction of his palm, sparks, some quite large, flew from his hands to the beam. His machines enjoyed overnight popularity and, not surprisingly, many electrical effects were discovered with their help.

An unusual event happened in the famous Leyden labo-

ratory. A student called Cuneus used von Guerike's machine to charge the water in a glass flask with electricity. The charge was delivered through a chain attached to a beam on the machine and lowered through the neck of the flask into the water. Cuneus was holding the flask in his hand; after a time he decided to remove the chain from the water with his free hand. When he touched it he received an electric shock, from which he nearly died.

It was found that a very great deal of electricity could accumulate in vessels like that. The 'Leyden jar', the simplest form of condenser, had been discovered.

News of the new invention quickly spread through Europe and America. In all the laboratories and aristocratic salons amazing experiments were put on which were at once unpleasant, amusing, and mysterious.

The French capital naturally had not remained aloof from the Leyden craze. Seven hundred Parisian monks held hands; as soon as the first monk grasped the neck of the jar all seven hundred were seized by a single convulsion and cried out in terror. Despite the unpleasant sensation thousands of people wanted to have a go at this experiment. New, more powerful jars were prepared.

The Leyden jar became an indispensable item for many experiments and made it possible to obtain electric sparks several centimetres long.

The most far-sighted concluded that the forked lightning that split the stormy sky was also an electric spark, only on a grandiose scale, produced by a giant Leyden jar.

The man who demonstrated it was Benjamin Franklin. It is difficult to imagine a more remarkable and popular personality of that day. He was born in 1706 in Boston and lived to 84. He only concerned himself with physics for the seven years between 1747 and 1753, after hearing a lecture on electricity at which an electric spark was discharged and the unpleasant effect on man of the charge from a Leyden jar was demonstrated.

Franklin gave science the concepts of negative and positive electricity. When we use the words 'battery', 'condenser', 'conductor', 'charge', 'discharge', and 'winding' we seldom remember that it was Franklin who first gave all these objects and phenomena their names.

In his last years he was one of the most eminent figures in the political life of America and an active fighter for America's liberation from England's colonial yoke.

At twenty-seven he was the most popular writer in America. His *Almanacks*, widely known as Poor Richard's because of his pseudonym Richard Saunders, came out annually in large editions.

'I might in this place attempt to gain thy Favour,' he wrote frankly in the preface to one, 'by declaring that I write Almanacks with no other View than that of the publick Good; but in this I should not be sincere; and Men are now adays too wise to be deceiv'd by Pretences how specious soever. The plain Truth of the Matter is, I am excessive poor... The Printer has offer'd me some considerable share of the Profits...'

He was one of the most charming and educated men of his time, gay, full of vitality, and physically fit, and always surrounded by interesting people, diplomats, and scientists.

But let us go back to his seven 'electrical' years, or rather to those concerned with his proof of the electrical nature of lightning.

After his chance hearing of the lecture Franklin developed a quite simple but elegant and correct theory of static electricity and of how it was transmitted from one body to another, the same theory we learn at school when we are first introduced to electricity. Only one correction needs to be made now; Franklin took it for granted that the body that accumulated electricity had a positive charge and that the body that lost it a negative one. We now know that the negatively charged electron is the bearer of electricity

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in conductors. Therefore, in our view, the electrified body must be identified as negative. Franklin naturally could not have foreseen this; in order not to destroy the established view, held since his time, the direction of current (from 'plus' to 'minus') is now accepted as the reverse of what happens in the actual process, i.e. in the movement of electrons.

Franklin's clear ideas about the nature of electricity helped him to develop a theory that represented lightning as an electric spark. In one of his works he described how one should set about demonstrating this experimentally.

A Frenchman Dalibard set up a device in Marly for the experiment suggested by Franklin: he fixed a metal rod on a hill so that one end of it could be brought close to a stake in the ground. During a thunderstrom on 7 May 1752 Dalibard got a large blue electric spark from the thundercloud, accompanied with a bright flash and the smell of ozone. Eight days later he demonstrated it to the king.

Though Dalibard was the first to coax lightning from the sky, it is clear that it was Franklin who was the real discoverer. In 1753 he made his famous experiment with a kite.

In the same year Michael Lomonosov and G. V. Richman made similar experiments. Richman wanted to measure the electrification in a bolt of lightning. He negligently bent too close to the rod of his 'thunder machine' and was struck on the head by lightning. Here is how Lomonosov described his attempts to bring Richman back to life: 'The first shock from the line suspended on a thread got him on the head and a cherry-red spot appeared on his forehead. The vast electrical force passed out of him through his feet into the planks. His feet and fingers were blue and his boot was ripped but not burnt through....

'The doctor and philosopher C. G. Kratzenstein arriving, massaged the scientist's body with Hungarian vodka, bled him, and pinching his nostrils, blew into his mouth so that

breathing might be brought into movement. All to no avail. Sighing, he pronounced him dead.'

Franklin, properly comprehending the electrical nature of lightning, invented the lightning rod (or possibly repeated a more ancient invention), which has saved thousands of lives and a great many buildings.

There have always been many weird tales and cock-and-bull stories about lightning. The famous French astronomer Camille Flammarion wrote in one of his books *(L'Atmosphère)* of a very hairy man, caught in a thunderstorm, having the hair shaved off by lightning in strips all over his body, rolled into balls, and thrust deep in the muscles of his calves.

Flammarion also told a story about a certain Dr. Drendinger of Vienna who lost his purse (or rather had it stolen) as he was returning home by train in the summer of 1865. The purse, made of tortoise shell, had his monogram, two intertwined 'D's', set in iron on the lid. Some time later the doctor was called out to a foreigner who had been 'killed' by lightning. He found him unconscious under a tree with the doctor's monogram branded on his thigh. The 'dead man' was brought round and taken to hospital. The doctor said the hospital people would find a tortoise-shell purse somewhere in the man's pockets. His prediction was correct; the man proved to have been the thief who had stolen the purse. The lightning had branded him with the metal monogram.

In an old Russian encyclopaedia there was an account, in the volume on electricity, of lightning having struck the earth between a cellar and a cistern near Manchester on 2 August 1809 and 'moved a wall a yard thick and more than twelve feet high, in such a way that part of it was shifted more than three feet in one direction and ten feet in another, all the wooden connecting sections being destroyed. More than 7000 bricks were displaced, weighing in all around 26 000 kilograms.'

It has been reckoned that in thirty-three years in the eighteenth century in Germany 170 bell-ringers were killed and 400 bell towers damaged by lightning. So many bell-ringers being killed could not have been a fluke. Man's natural defence against lightning at that time was the ringing of a bell, which drove away evil spirits. When a thunderstorm began bell-ringers were generally sent up the bell towers to ward off the spirits. The bell tower was generally the highest building in a place and was therefore naturally the first target for the giant spark from the charged cloud (the spark would sometimes be tens of kilometres long). But no one felt sorry for the ringers; it was thought that lightning was a weapon of retribution in the hands of Providence and it was a sin to oppose it, they were its main victims. That a lightning conductor does to some extent protect bell towers can be seen from Solomon's Temple in Jerusalem which was not once damaged by lightning over a thousand (!) years; it was roofed with metal tiles.

After 1760 when Franklin had put the first lightning rod on the house of Mr. West, a Philadelphia merchant, Europe and America were divided into two camps: that of those who ardently favoured lightning conductors and that of those who equally ardently opposed them. At one time in Paris it even became fashionable to wear hats with lightning rods. About the same time, de Viseri, who had erected a conductor on his house in Saint-Opéra, was exposed to the violent opprobrium of his neighbours, who eventually, in 1780 brought an action against him that dragged on for four years. A still unknown lawyer Maximillian Robespierre appeared as defence counsel for the lightning conductor; the expert Jean Paul Marat appeared on behalf of its opponents. In the end de Viseri won his case, but Frenchmen opposed conductors for a long time. And they might have gone on doing so for much longer but for a rather curious event.

By 1782 400 houses in Philadelphia had been fitted with lightning rods (the town had only 1300 houses all told). The roofs of all public buildings, with the exception, of course, of the French Embassy, were crowned with their metal points. During a thunderstorm on 27 March 1782 lightning hit precisely this exception; the Embassy was partially destroyed and a French officer living in it was killed. This event had a great effect on public opinion and after it lightning conductors were fitted on all buildings. And they were recognized even officially by France.

It was possibly only after these momentous trials and events that the electrical nature of lightning was generally accepted. There was no longer room for any doubt that lightning was an electrical phenomenon. The connection between lightning and electricity had been firmly established. About the same time scientists began to move gradually toward the idea that lightning was also in some way connected with magnetism. But that was a big hurdle to jump, largely because there was very little systematic information about magnets.

What unknown, mysterious force controls the needle of a compass? What forces give an inanimate stone the capacity to move as if it were animate?

It is hardly surprising that the philosophers of antiquity explained the unusual qualities of magnets by their being divine. Verses were written about them, ascribing hundreds of the most incredible qualities to them. In particular it was thought that they were created by evil demons for the ruination of people, and for the benefit of thieves and robbers because magnets had the power to open locks and bolts.

Magnetism had medical applications without number. One of William Gilbert's remedies (you will remember he was physician-in-ordinary to Elisabeth I) was for preparing iron for chalybeate medicine. He advised taking the best iron, chalybean, steel, or siderite and sawing it

down to a very fine powder. The powder was then steeped several times in very strong vinegar and dried each time in the sun, and then washed in spring water, or other suitable water, and once more dried. It was then again reduced to a powder by pulverizing it on a porphyry slab, passed through a very fine sieve, and stored for use. The powder was administered to patients with swollen or too humid livers, or enlarged spleens. It restored health and beauty, Gilbert said, to girls suffering from paleness or bad colour, because it dried and bound without causing harm.

By 'iron' Gilbert meant magnetite or loadstone, the only magnet known in the Middle Ages. He cautioned against using it as a penacea for all ailments. He considered magnet to have a dual nature, mainly noxious and pernicious. And though, in its pure form, it occasionally not only could be harmless but also had the capacity to put over-humid and putrefying intestines into order and improve their condition, in most cases daily experience, and the weakness and death of patients convinced even the most negligent and slothful physicians of its harmfulness.

The doctors of classical times, and Gilbert, and even some of our modern doctors, held similar views on magnets having a suppressive effect on the nervous system, neutralizing its activity. This property could naturally be put to good use. Even in antiquity the Aesculapii had noted that magnets reduced pain in the wounded, gave relief to headaches, and helped in the treatment of diseases like epilepsy connected with heightened activity of the nervous system. As for the effect of a magnetic field on the healthy, scientists are no less divided today than they were several centuries ago.

You may have seen friends wearing 'magnetic bracelets' or heard of the 'magnetic armchairs' and 'magnetic beds' made by Japanese firms. Japanese scientists maintain that wearing such bracelets lowers the blood pressure. But it is difficult to say which has the greater effect—the magne-

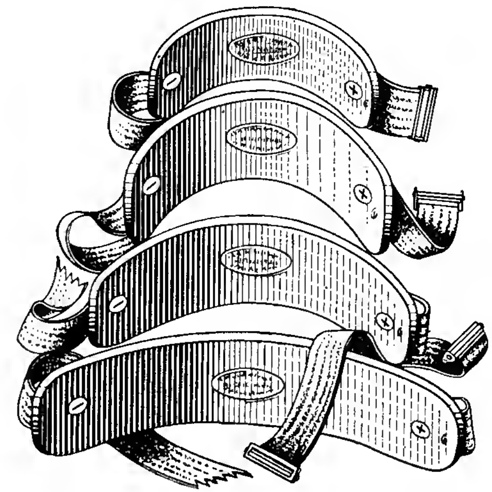

Fig. 7. Magnetic breastplates were mass produced in the nineteenth century in various sizes, much as with clothes and shoes.

tic field or the auto-suggestion. In the history of medicine both ancient and comparatively modern one can find numerous cases of doctors who not only recommended their patients magnetic bracelets but also advised them to put magnetic plates on their feet, head, neck, and chest (Fig. 7).

Soviet physicians and cardiologists who were the first to investigate the supposed curative qualities of magnetic bracelets, belts, armchairs, etc., concluded that none of these inventions were an effective means of treating hypertensive disease, a view now held by many scientists abroad, including Japanese. Taking all this into account, the Collegium of the USSR Ministry of Health proposed dropping tests with magnetic bracelets and did not recommend either their production or their use.

In antiquity there was another field in which magnets were used—conjuring. Then, and in the Middle Ages, a trick very much in vogue was 'the obedient fish'. The fish were made of wood and swam in a basin, obeying the slightest movement of the conjurer's hand, which made them move about in every conceivable direction. The secret of the trick was extremely simple: the conjurer had a magnet hidden up his sleeve and in the head of each fish was a little piece of iron. You can still buy a variant of the game today.

Another modern variant is the small but powerful magnets sold in some countries for recovering objects from the bottoms of ponds and reservoirs.

Some years ago a group of adventure-seekers lowered such a magnet over the side of their launch after a race near the Bahamas. The boat suddenly lurched and pulled up sharply. Divers searched the bottom near the spot where they had stopped and discovered that the magnet had been attracted by the anchor of a Spanish galleon sunk by pirates off the Bahamas in the seventeenth century. While inspecting the ship the divers discovered a chest full of gold and silver plate for rich families in the New World. Archaeologists use similar magnets not for treasure hunting but in searching for the traces of ancient civilisations.

But to return to conjuring, the most recent use of magnets we recall was in the sleight-of-hand of an English conjurer called Jones. His crowning number was to ask members of the audience to put their watches on a table. Without touching them he was able to alter the position of the hands at will—naturally, by means of a magnet. Electromagnetic clutches, with which electricians are very familiar, are the modern equivalent of the same idea. They can be used to turn equipment separated, for example, from the motive force by a wall.

It is still not clear how Gamuletsky, the famous Russian illusionist, performed his trick with a magnet in his

'Temple of Charms or the Mechanical, Optical and Physical Cabinet of M. Gamuletsky de Kolla'. His study, which existed until 1842, had a further attraction; as visitors mounted the carpeted staircase past the decorated candelabra, they could see from a long way off on the top landing the life-size gilt figure of an angel hover above the study door with no visible support or suspension. (Anyone who so wished could check that the statue had no support whatsoever.) And when visitors stepped onto the landing the angel raised its arm, put a horn to its lips, and 'played, moving its fingers in a most natural manner'.

Gamuletsky explained that it took him ten years to find the point and the weight of magnet and iron that would support the angel in the air; and that he had put a great deal of money as well as effort into the marvel.

No more suitable role than conjurer's prop could apparently be found for the mysterious magnet.

A great many explanations have been advanced at various times as to why a magnet and a piece of iron should experience such a strange attraction for each other.

In the songs of Orpheus there are some lines about how iron is attracted by a magnet like a bride by her betrothed.

The philosopher Epicurus explained it much as follows: the shape of the atoms and indivisible bodies, flowing from stone and iron, so suited each other that they were easily coupled together; so, on striking the hard parts of stone and iron and bouncing off toward the centre they immediately came into contact with each other and attracted iron.

And Plato, the idealist, wrote that, in view of the fact that a vacuum never exists, bodies jostled each other from all sides, and when they separated and united, they all, having changed places, crossed to their normal places; and that those who carried out a proper investigation would probably be brought to confusion by involved inter-relationships.

In speaking about 'involved inter-relationships' Plato

was surprisingly far-sighted. Subsequent discoveries convinced scientists that the nature of magnetism was much more complex than the mechanistic notions of the ancient philosophers, who reduced the problem to one of the 'engagement' of particles.

As with electricity it was lightning that put scientists' thinking about magnetism on the right path.

Early in the nineteenth century the French scientist Arago published some curious notes on thunder and lightning, which probably led to his friend Ampère, the physicist, becoming the first to provide a correct explanation of magnetism.

In July 1681, Arago wrote among other things, the ship *Quick* was struck by lightning. When night fell the position of the stars showed that two of its three compasses, instead of pointing north, were pointing south, while the third pointed west.

Again, in June 1731 in Wakefield, a merchant put a large coffer full of knives and forks and other iron and steel objects in the corner of his room. Lightning penetrated the house exactly in the corner where the coffer was, smashed it, and scattered all the things inside it. All the knives and forks became very strongly magnetized.

It became increasingly obvious that lightning and magnetism were very closely connected. Since the link between lightning and electricity was already well known, clearly the most perspicacious would soon see the link between electricity and magnetism. Many had almost guessed the connection, and it only required a little more effort to bridge the gap dividing the two great forces of nature.

On 7 September 1758, at a general meeting of the Russian Academy in St. Petersburg, Franz Ulrich Theodore Epinus read his treatise *On the Similarity Between Electrical and Magnetic Forces* and came close to solving the problem.

All that was needed was a link, a connecting thread.

Sir Humphrey Davy, the famous English scientist, also

very nearly solved the problem. He established that an electric arc is deflected by a magnetic field. Here was the connection, albeit tenuous, but it was not given the necessary significance.

Only a very persistent and very purposeful person could find the solution. This man was the Danish physicist, Hans Christian Oersted, who investigated the connection between electricity and other known phenomena like light, heat, and sound. Only one connection eluded him, that between electricity and magnetism. Nothing, it seemed, connected these two forces, and each existed independently of the other and in no way connected with it.

But lightning? Now that seemed to bind electricity and magnetism together in the closest way! And Oersted searched continuously for this elusive connection. It is said that he always carried a magnet about with him to remind him of his complex problem. His efforts were in vain—till suddenly everything changed. He nearly solved the problem in a single day, on 15 February 1820.

On that day Professor Oersted was lecturing on the connection between electricity and heat to his students at the University of Copenhagen. We are all now familiar with electric stoves, immersion heaters, and electric blankets, which employ the heating effect of electric current; but then it was completely unknown, and the fact that wires carrying electricity became hot caused a great deal of excited curiosity.

Two fortuitous things occurred: first there happened to be a compass by the wire being heated and second, during the lecture, a student (whose name we do not know) happened to glance at the compass, which had nothing really to do with the lecture. He was very surprised to notice that when a current flowed along the wire the needle of the compass was deflected. The electric current had created a magnetic field!

After that events developed like wildfire. In a few days

the French scientists Arago and Ampère had built a device that gave the same sort of magnetic field as a permanent magnet made of magnetite or magnetized iron. This device, later called a solenoid, was simply a spiral along which a current flowed.

The similarity between a magnet and a solenoid, which is a large number of coils bearing current, led Ampère to an inspired guess: inside a magnet were a large number of miniature circuits. This theory has been brilliantly confirmed: electrons revolving around nuclei form circuits. A new era in the understanding of magnetism was opened.

ELECTROMAGNETS WITH STEEL CORES

Magnets on Parade

Wherein we talk about the rivalry between magnet-makers in various countries.

The first electromagnet in the world was demonstrated to the Royal Society of Arts by William Sturgeon on 23 May 1825. It was a varnished iron rod a foot long and half an inch in diameter that had been bent into a horseshoe and covered all over with a single layer of uninsulated copper wire. Current was fed to it from a chemical source. The electromagnet weighed 200 grams-force but was able to support a weight of 3600 grams-force, and was considerably stronger than natural magnets of the same weight. It was a brilliant achievement for the time (Fig. 8).

James Prescott Joule (after whom the unit of energy is named) was a student of Sturgeon's. Experimenting with Sturgeon's first magnet later the same year he was able to increase its lifting capacity to 20 kilograms-force.

Sturgeon was not prepared to lose his lead in exploiting his own invention. In 1830 an electromagnet was built to his order capable of lifting 550 kilograms. But he already had a very strong rival on the other side of the Atlantic. In April 1831 Prof. Joseph Henry of Yale University (after whom the unit of inductance is named) built an electromagnet of 300 kilograms-force and able to lift around a ton.

These magnets consisted of a horseshoe core around which a wire was wound. In November 1840 Joule designed and built a magnet consisting of a thick steel tube cut along the

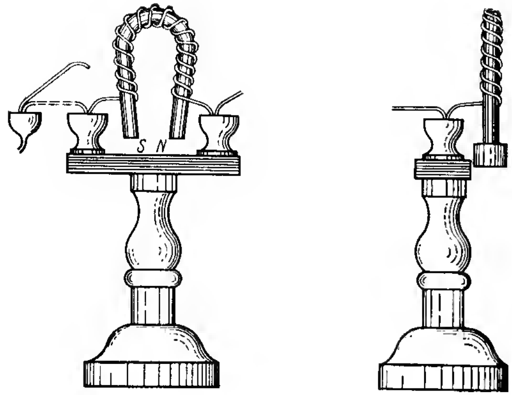

Fig. 8. The world's first electromagnets were made by the English craftsman William Sturgeon.

axis below the diameter. The magnet itself was quite compact yet proved to be very powerful, lifting 1.3 tons. About the same time Joule built a completely new type of magnet that attracted a load not by the usual two poles but by a much larger number, which greatly increased its lifting capacity. His magnet, which weighed 5.5 kilograms-force lifted a weight of 1.2 tons. Electromagnets began to appear in great numbers in physics laboratories, in aristocratic salons, and in doctors' surgeries. They even began to be used in clothing factories (in the machines) and in concert halls (as a part of the 'magnetic organ'). By 1869 magnets were already widely used as a drive for Jacquard looms and for punching holes in metal plates.

A little later, when several more large magnets had been built and everyone was convinced of their strength, reliability, compactness and convenience, it was suggested that they be used to lift iron and steel items in steel works and

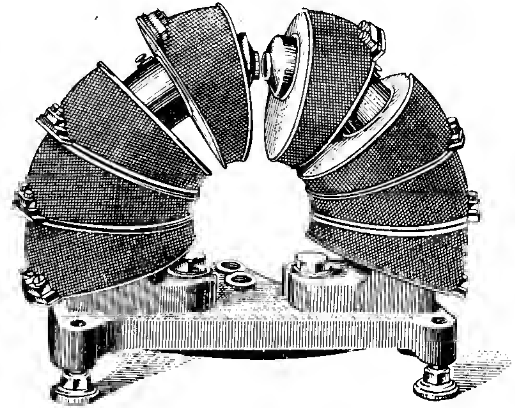

Fig. 9. An old electromagnet.

engineering factories. In the 1930's a very large electromagnet was built for equipment to destroy defective castings. Its load was an iron ram weighing 20 tons. The advantage of the electromagnet was that the ram could be dropped simply by switching off the current. Even more powerful magnets were soon built, capable of lifting 50 tons. Their power was growing hourly.

In Europe and America magnets became widely used in flour mills to clean the grain. And in Russia, at the turn of the century, the Horse-Tram and Omnibus Company used them to remove nails from the oats fed to the horses.

The cleaning of grain in flour mills became the prototype of one of the most important of today's applications of magnets, of what are called magnetic separators. These function on the principle of passing a mixture of useful material and rubbish on a conveyer belt past the poles of a magnet. Any rubbish that is magnetic is pulled out of the mixture. The principle was first proposed as far back

as 1792, long before the invention of the electromagnet. It is now used in many branches of mining, particularly in coal mining, where it is beginning to rival the 'wet' method of concentration.

Almost everywhere coal is concentrated in special jigging or flotation plants. Both methods are wet processes because the concentration occurs in water; as a result both the waste and the concentrated coal are saturated and have to be dried. A great deal of water is required (thousands of cubic metres) and there are problems of cleaning the polluted water and of preventing the particles from freezing in cold weather.

Almost all the harmful admixtures in coal are magnetic, so that it is possible to avoid using wet processes by putting a ribbed, magnetic roller in the path of the belt conveying the pulverized coal. The roller attracts and removes the impurities. This method of cleaning, first proposed and tested in the Soviet Union, reduces the ash content of coal fines from between 12 and 17 per cent to around 7 or 8 per cent.

How can rocks like pyrites, which are not magnetic, be removed from the coal? Scientists have also found a way: the pyrites are treated in a mixture of air and steam at 270°-300°C and covered with a layer of magnetic oxides.

In the 1880's Thomas Edison invented another type of separator. The story goes that, on a daily morning walk, strolling along the shore of Long Island, he noticed that the sand on the beach contained tiny bits of iron oxide. If you sprinkled it between the poles of a magnet it might be easy to divide the non-magnetic particles from the iron oxide. Edison's idea solved one of the problems they were facing at that time, namely, what to do with ore deposits with a low iron content. He suggested treating the ore so as to make it like the easily separated sand on the beach, in other words, to grind it. After grinding in a crusher the ore is passed to a tower and poured from the top. As the

particles fall they meet the fields of several powerful electromagnets of increasing intensity. The magnetic iron oxide settles on the magnets and is periodically removed from them. The gangue falls to the bottom without hindrance. It is hardly surprising that the town that arose on the 'poor' deposits was called Edison City.

Magnetic separators are also used in agriculture to free clover, flax, and lucerne seeds from weeds. Engineers have turned the enemy's weapons against him. The seeds of weeds (like bitterling and rye grass darnel) are rougher as a rule and covered with tiny spikes that enable them to stick to clothing and animals and so promote their rapid spread and struggle for survival. When fine iron filings are strewn on seeds contaminated with weeds, they stick to the weed seeds while the smooth grain remains clean. Then, by using a magnetic separator of some sort, the grain can easily be cleaned.

A very similar method is also used for catching criminals. The sweaty, greasy finger-prints the criminal leaves at the scene of the crime are often very faint and more often than not are on material with a coarse texture (planks, veneer, or cardboard). The criminologist V. I. Sorokin suggested using a 'magnetic brush' instead of dusting the prints with coloured powders as used to be done. The brush is a small magnet with narrow poles, which is passed back and forth in various directions over the surface being examined. The magnet is first put into a dish of very fine iron filings, which cling to the poles in the normal way. As it is passed over the dirty surface the filings, which act as the 'bristles' of the 'brush', adhere to the sweat and grease of the fingerprint and colour it a characteristic dark grey; the rest of the surface remains clean. The prints brought out by the filings are readily copied on special film.

Lifting magnets are widely used in industry and other fields where a specially strong force of attraction is required. When Professor Auguste Piccard, for example, explo-

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red ocean deeps in his famous bathyscaphe, a powerful electromagnet supported its iron ballast.

Electromagnets are also used in transport. As early as 1910 railway engineers magnetized the wheels of wagons in order to improve grip on the rails (by increasing friction). The electromagnet tripled the coefficient of friction, and consequently the load capacity.

This, of course, is by no means the whole extent of the application of magnets in transport. There is, for example, Weinberg's famous scheme for a magnetic road, a tube along which small wagons suspended in a magnetic field would move in a vacuum, attaining very high speeds (of the order of 1000 km per hour). Small models of his system were built, and were used at one time to transport letters at the Moscow Post Office.

Great advances have recently been made in the United States on the magnetic suspension of trains, in particular with Francis Bitter's magneplan at the National Magnetic Laboratory, which develops a speed of 300 miles an hour.

It is also planned to use electromagnets for docking spacecraft. Magnetic boots for spacemen would be another not unimportant development.

But to make a magnet that is good enough, powerful enough, and with all the required characteristics is not so simple. First of all it must be correctly designed, and that didn't happen at once. And naturally, before electromagnets could be brought into general use in industry, transport, and other fields, they had to be tested in the laboratory.

The first magnets were made 'trusting to luck'. Not every shape, however, produced a good result. It was purely accidental that Sturgeon chanced upon a very successful one; horseshoe magnets have been made ever since. Lack of experience and of any elementary method of designing magnets led to shapes that now seem quite absurd.

A three-pronged magnet, for instance, could not work properly because the magnetic fluxes in each prong would

largely counteract each other—the current in one would form a circuit with the second where it would act in the opposite direction to the actual current in that prong.

The type of magnet that used to be made, consisting of three smaller magnets wound separately, was once very popular but today is thought useless, because the fields of two neighbouring magnets cancel each other out in the space in between them.

Laboratory magnets used to be made by eye. There was no theory that made it possible to predict their properties in advance. The Russian scientists E. K. Lentz and B. S. Jacobi made the first contribution to a theory of magnetism, by pointing out the connection between the lifting power of an electromagnet and the product of the current in coil and the number of turns in the winding. Following Lentz and Jacobi the Englishmen John and Edward Hopkinson made an enormous contribution to the theory of designing magnets with their proposal of a method for calculating 'saturation', a phenomenon that had long been noted by the designers of magnets. A magnet of given shape has a certain limit after which it is impossible to improve its lifting capacity significantly by increasing the current in the coils. Modern theory links this phenomenon with the fact that when a magnetizing current reaches a certain limit all the previously haphazardly ordered elementary magnets in the iron now lie in one direction, and further increase has no effect. The saturation of steel prevents the magnetic field of primary magnets from exceeding 20 000 gauss.

A new era of more powerful magnets was opened, based not on increase in their size but on improvement of their shape and on combating saturation. It cannot be said, however, that the struggle against saturation was very successful. In the hundred years of the physicists' war the inductance of the magnetic field was only a little more than doubled.

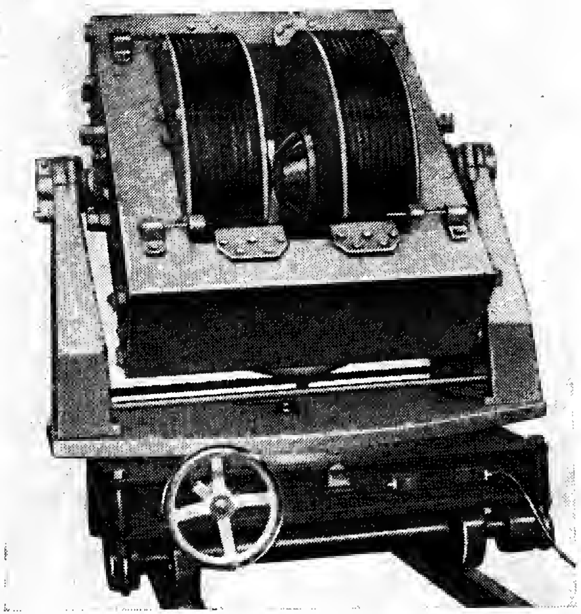

Fig. 10. Contempory Japanese M-50 magnet.

Leading physicists and electrical engineers like Faraday, Becquerel, and Thomson worked on the problem.

What could physicists counterpose to nature? Only very accurate calculations and full exploitation of the natural properties of the materials. So magnets were made with short conical poles, and massive yokes, and huge coils. They quickly increased in weight, mainly due to the increased weight of the coils. In 1881 the largest magnet in

any laboratory in the world weighed about a ton; by 1930 there was already one that weighed 120 tons.

Even in this way, however, they still did not succeed in increasing the inductance of electromagnets to, say, one million gauss. And such a field is still the physicists' unattained dream—primarily because of saturation.

Nowadays magnets are mass produced. They do not break records, but it is possible with their help to obtain the quite considerable field of 40 000 to 50 000 gauss needed for research from a medium-sized magnet weighing a few tons.

What are magnets used for in modern physics laboratories? They are needed for studying the behaviour of substances in strong fields, for research into galvanomagnetic, thermomagnetic, and magnetostrictive phenomena, and for obtaining super-low temperatures (only a thousandth of a degree above absolute zero) by adiabatic demagnetization. They are also used in quantum generators (masers), for analysing particles by their mass in magnetic mass-spectrometers, and for research into the interactions of atomic particles, and in medicine and biology.

Magnets are widely used in studying elementary particles. We are not thinking here of accelerators but of the instruments used to study the reaction products obtained by bombarding targets in them.

Every schoolboy now knows how a Wilson cloud chamber, one of the most important instruments for investigating nuclear processes, is built. Usually it is filled with moist, cleaned air. When a high-energy particle enters a chamber it disturbs all atoms along its path, knocking out the weakest electrons so that a positively charged path is formed in its wake. The positive ions that make up its track can become centres of precipitation of water vapour from the air in the chamber. So that the process can occur with greater intensity the air in the cloud chamber is allowed to expand suddenly. The ions of the 'trail' begin to be envelo-

ped by tiny droplets of water and a misty visible trail, rather like one left by jet aircraft, is formed, which can be observed and photographed. A particle, so small as to be unimaginable, becomes visible! So the cloud chamber enables us to follow the collision of particles and the formation of new ones. Atomic physicists cannot do without it.

But just as it is impossible to judge the type of jet aircraft by the trail it leaves in the sky, so it is also impossible to say exactly what sort of particle enters a cloud chamber from what is left behind. The answer to the dilemma was found by the Soviet physicist, P. L. Kapitza, and published in 1923 in a brief communication in the *Proceedings of the Cambridge Philosophical Society* in which he described several experiments allowing observation of the tracks of particles in a cloud chamber. His arrangement differed from Wilson's in that the chamber was placed in a strong magnetic field.

What did that give? It revealed that in a magnetic field a charged particle moved in a curve, the radius of which was

$$r = \frac{mv}{H}$$

where m was the mass of the particle, v its velocity, and H the strength of the magnetic field.

Thus, by knowing the strength of a magnetic field and measuring the radius of the trail of a particle in a cloud chamber, we can ascertain its impulse (mv); and knowing its mass, we can determine its energy.

So long as the energy of the particles studied was relatively small, the Wilson cloud chamber was an indispensable piece of laboratory apparatus. But in the Fifties, in the USSR, the USA, and other countries, a series of giant accelerators were brought into service capable of imparting colossal energy to particles, an energy so great that particles passed through cloud chambers without hindrance and were scarcely deflected by the magnetic field (which is not sur-

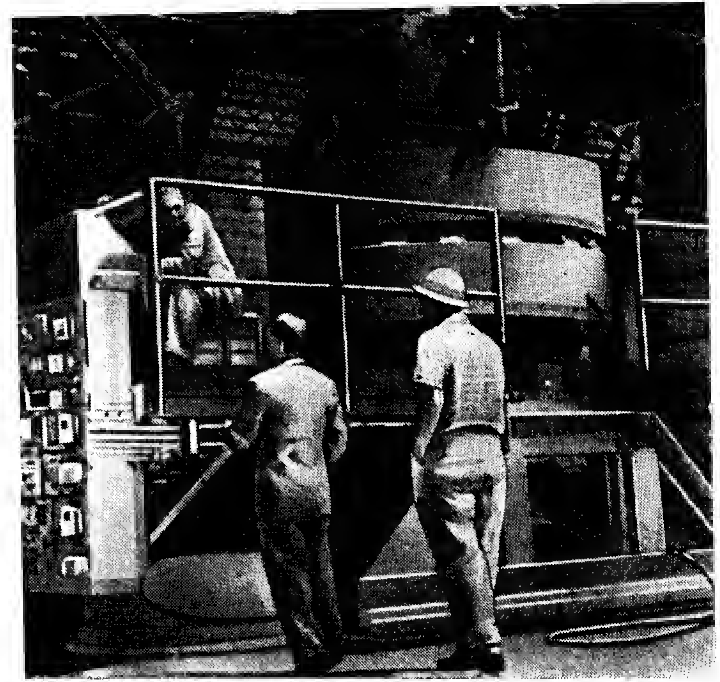

Fig. 11. A powerful bubble chamber. The yoke (on the left) and the coils of the electromagnet are clearly visible.

prising because the chambers were filled with gas, which offered almost no resistance to them). It became necessary to study particles in some other way.

A 'bubble chamber' was suggested, which could also be called an 'anti-cloud chamber'. In the Wilson cloud chamber the track of a particle consists of tiny droplets of liquid condensing on ionized atoms, whereas the track in a bubble chamber consists of tiny bubbles of gas formed in a liquid

medium by the heat given off during the formation of charged ions by an 'energetic' particle. Organic liquids or liquefied gases are usually used. The useful volume of bubble chambers varies from a fraction of a litre to hundreds of litres. And likewise the magnets used with them also vary (Fig. 11). For the Soviet freon chamber (diameter 115 cm; height 50 cm) for example, a magnet with a field of 26 500 oersteds, and weighing 72 tons, was made.

There are even bigger chambers and magnets. On one of the anti-proton channels of the synchrotron in Dubna, not far from Moscow, there is a propane chamber, one of the largest, with a diameter of two metres.

At the exit of the Serpukhov accelerator the very large French Mirabelle bubble chamber, with a functioning diameter of five metres, has been installed.

But physicists are drawing up new schemes, and a liquid hydrogen chamber with a diameter of seven metres is on the drawing boards waiting its turn for use in studying that all-penetrating particle, the neutrino.

HIGH-FIELD MAGNETS

Electromagnets Without Steel Cores

A chapter about magnets with fields half a million times as strong as the Earth's, and about waterfalls, and the fission of uranium, and forces that annihilate each other.

A place of honour in the history of building powerful electromagnets belongs to the American physicist Francis Bitter. He was born in Weehawken, New Jersey, in 1902. At 28 he got his Ph.D. for research into the magnetic properties of gases. He then joined the Westinghouse Company, where he worked on theoretical and engineering problems of magnetism. Later he took up teaching at the Massachusetts Institute of Technology, where he built his famous 'Bitter' solenoids. His whole life was dedicated to the study of magnets and magnetism. Even during the war he continued his favourite research, working on magnetic mines and defences against them.

Bitter built the most powerful electromagnets of his time. In the thirties he needed a powerful magnetic field of approximately 100 000 oersteds for his research into the fine magnetic phenomena in gases and had to build a magnet quickly that would sustain this terrific field, 200 000 times that of the Earth, for a long time, a matter of several hours.

Before starting on the job, however, he decided to review everything that had been done before him in this field.

Very powerful experimental electromagnets with steel

cores were then working in Bellevure, outside Paris (with a field up to 60 000 oersteds), and at Uppsala University in Sweden (with a field around 70 000 oersteds). These were huge affairs with magnetic steel cores and a yoke, classical magnets weighing around 100 tons.

Bitter also knew that it was very expensive to induce a field as high as 60 000 or 70 000 oersteds. Compared with compact, ordinary magnets with field of 30 000 to 40 000 oersteds and weighing around a ton, the magnets in Paris and Uppsala were like enormous, prehistoric monsters. There was no point even in considering how to obtain a field of 100 000 oersteds by using an electromagnet with a steel core, although theoretically it could easily be shown that there was no limit, despite saturation, to the strength of the field obtainable from steel magnets. An infinite field would be possible if the whole Universe, with the exception of the point where the magnetic field was created, were completely filled by magnetized iron.

Francis Bitter was well aware that, to get a field of 100 000 oersteds, he would have to fill perhaps not the whole Universe but at least his whole laboratory with saturated steel. Steel cores were simply out.

Another method had been known since the days when Arago and Ampère invented the solenoid. The unpleasant properties of this method had been formulated by the French electrical engineer Charles Fabry and expressed in the Fabry formula, published in 1898 in the journal *Eclairage électrique*. This formula, which has withstood the stormy onslaughts of the twentieth century, is:

$$H = G\sqrt{W\lambda/\rho a}$$

where H is the strength of the magnetic field of the solenoid in oersteds; G is a coefficient (the Fabry factor) equal to 0.1-0.29; W is the power dissipated by the solenoid in watts; λ is the ratio of the volume of the bare conductors to the total volume of the coils; ρ is the specific resistance or resistivity of the material of the coils, in ohms per centimetre; and a is the inside radius of the solenoid, in centimetres.

What does the Fabry formula tell us? It shows that if we want to make a magnetic field ten times stronger we must increase the power dissipated in the solenoid by 10^2 or 100 times. Whole power stations would be needed to obtain strong magnetic fields. In 1923-7, when Kapitza obtained a field of 500 000 oersteds, he was not faced with this difficulty because his field only had lasted 0.001 second. And his method, too, was of no use to Bitter, who wanted fields of long duration.

The only solution open to him was to have a powerful solenoid without steel. In 1936 he went to the Edison Electric Company in Boston and persuaded the directors to release power to him during the hours when the city slept peacefully, so that he could try out his voracious magnet. The magnet, about the size of a motor-car tyre (by intense cooling he had been able to make it small), was installed in one of the power station's buildings. When he switched it on for the first time something quite unbelievable happened: from all corners of the room fine iron dust, iron filings, nails, and small bolts hurtled toward the little bronze box, to which led two big water-pipes carrying cooling water from a heat exchanger washed by river water. The magnet in fact consumed around 1.7 megawatts of power, almost converted into heat, which had to be dissipated in order to prevent the temperature from rising. (If it were not washed with cooling water at a rate of 50 litres a second it would burn out.)

Bitter designed his own original magnet. It proved so successful that solenoids designed on the same principle are called after him. The first Bitter solenoid, with which a field of 100 000 oersteds had been maintained for a considerable time, was a series of stamped copper discs with a radial slit and 600 holes for cooling water. The slit made it possible by bending each disc slightly to join it to the

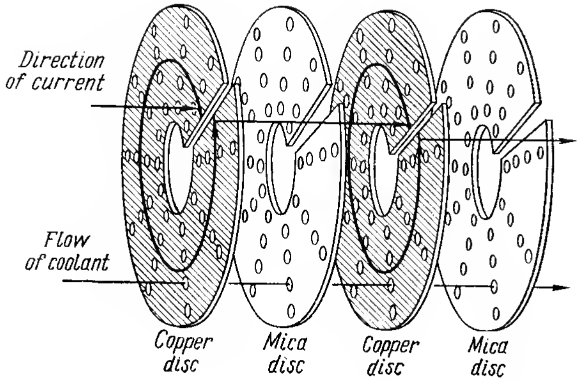

Fig. 12. The principle of the Bitter solenoid.

next one and thus make an unbroken spiral carrying a current (Fig. 12).

Being then the most powerful solenoid in the world, it was in constant demand for science up to the time research began to require even stronger fields. The only interruption came during the wartime Manhatten Project, when it was employed at Oak Ridge for experiments in separating uranium isotopes. Natural uranium contains only 0.7 per cent of U^{235} which was needed for the atomic bomb; Bitter's powerful magnet was used to separate U^{235} from the natural mixture.

The rapid development of many branches of physics in the 1960's, especially magnetic retention of plasma and study of superconductivity, antiferromagnetism, quantum optics, and elementary particles, made super-powerful magnetic fields a basic requirement. Special laboratories and institutes were set up in the USSR, the USA, and Great Britain to obtain them.

In 1965 a field of 220 000 oersteds was obtained, i.e.

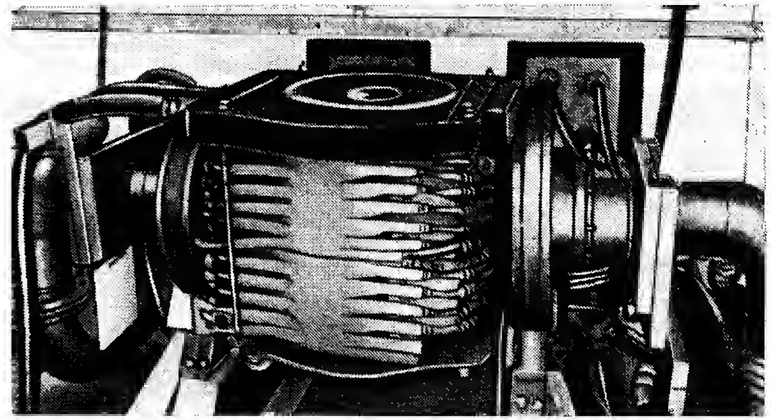

Fig. 13. The world's most powerful electromagnet in the US National Magnetic Laboratory

500 000 times stronger than that of the Earth, 100 times greater than that of sunspots, and only a quarter that calculated to exist in the atomic nucleus.

This field was obtained at U.S. National Laboratory of Magnetism by means of three co-axial solenoids, built by Henry Kolm, using Bruce Montgomery's design. The magnet had an inside diameter of ten centimetres and used 16 000 kW of power. The outside was wound with a hollow copper tyre of square cross-section. The inside was filled with copper discs, on which radial cooling channels had been etched.

More than three tons of copper were used in the magnet; and the pressure of the magnetic field inside it was so great that the copper began to 'flow'. The pressure, incidentally, was more than three times that at the bottom of the deepest ocean deeps.

The magnet had an interesting cooling system that employed the latest advances in building atomic reactors.

The solenoid designed by Montgomery employed the principle of 'film boiling'. The temperature on the surface of the cooled copper spiral, being over 100°C, caused numerous tiny bubbles of steam to form, which were dispersed in thousandths of a second in the huge volume of comparatively cold water that poured like a waterfall onto the solenoid.* Because the specific heat of vaporization of water is very great, much more energy was dissipated by the bubbles developing on the surface of the spiral than would be the case with heating of the cooling water. This principle of 'local' or 'film' boiling was first used in Kolm's small magnet that yielded a field of 126 000 oersteds. Compared with Bitter's 100 000 oersted solenoid it was tiny, only one-twenty-fifth the volume.

The magnets of 400 000 oersteds built in America and of 700 000 to one million oersteds built in the Soviet Union are cooled on the same principle. The power required by the Soviet magnets is colossal, 1000 megawatts, equal to the output of two of the generators in big hydro-electric stations like that at Krasnoyarsk.

The huge field of 220 000 oersteds obtained by Kolm occupied a comparatively small volume, although the magnet itself was more than a metre wide. Large-scale research was difficult with it and therefore designers have been searching for new ways of obtaining strong fields in significant volumes.

Perhaps another cooling agent could be used?

An interesting experiment was carried out at the University of California. A solenoid cooled with kerosene had already been built in 1959. Kerosene was used because water, especially water with impurities, is not an ideal insulator, and at a certain voltage its electrolytic properties begin to make their effect so that water-cooled coils corrode.

* We say 'waterfall' deliberately. A river not far from the laboratory was used to cool the magnet. The energy dissipated in the solenoid was so great that the water in the river below the laboratory was 0.5°C warmer than the water higher up stream.

Analysis of the suitability of other liquids as cooling agents showed that refined kerosene enclosed in a vessel filled with a neutral gas was the best as regards heat capacity, cost, and damage to the coils.

The kerosene solenoid, with an inside diameter of ten centimetres, was wound with a copper bus bar. It used 6000 kW of current and 100 kilograms per second of purified kerosene, and produced a field of 100 000 oersteds. It was installed in a special gallery 2.5 metres wide and 23 metres long. All fastenings—bolts, nuts, frames, and other parts, within a radius of five metres were made of non-magnetic materials. And to avoid an explosion the whole gallery was filled with an inert gas.

Kerosene was not the only candidate for the role of 'best coolant'. As far back as the beginning of the century Kamerlingh Onnes and his colleagues in the Cryogenic Laboratory in Leyden were already studying the temperature dependance of electrical resistance of various materials as the temperature was lowered. They had expressed confidence at a conference then that it would be possible within a few years to construct a solenoid with a field of a million oersteds by subjecting the conductors to extreme cooling; but more than half a century had passed and not one scientist had yet succeeded in obtaining a stationary field of a million oersteds.

How had Kamerlingh Onnes and his colleagues come to this conclusion? They were studying the electrical resistance of various metals at very low temperatures (—100° to —250°C or approximately 170° to 20°K) and had found that resistance dropped sharply as the temperature fell. And in Fabry's formula, which was already known, electrical resistivity is in the denominator. When a new lowered resistivity was put in the formula it turned out that the field increased for the same expenditure of power. So Ka-

merlingh Onnes and his colleagues apparently had good grounds for supposing that a field of a million oersteds was not beyond the bounds of possibility.

They had, however, underestimated two things: first, low temperatures are difficult to obtain and require a considerable expenditure of energy; and second, as the magnetic field grows due to what is known as magnetoresistance, the electrical resistance of metal also increases, the effect of magnetoresistance being especially strong at low temperatures.

In one of his articles Kapitza presented the results of his checking of the idea proposed in his time by J. Perrin, of cooling solenoids with liquid air. To cool a solenoid with a field of 100 000 oersteds and a diameter of one centimetre it would be necessary to pass liquid air through it at 24 litres a second. A whole factory producing nothing but liquid air would be needed to ensure smooth operation of the solenoid.

Possibly because of these factors, possibly for other reasons, the development of low-temperature but not superconducting magnets ("cryogenic magnets" as they are sometimes called) was greatly retarded (Fig. 14).

The first attempt to use low temperatures to reduce electrical resistance was made in 1961 with an aluminium solenoid of 100 000 oersteds cooled with liquid neon (which has a boiling point of 27°K). The inside diameter of the solenoid was 30 cm and its length 200 cm and the total weight of its aluminium coils five tons. In view of its huge field it was considered one of the biggest, if not the biggest, in the world. It was intended for thermonuclear research and had 'magnetic plugs' at each end with a field of 200 000 oersteds. But it could only function for one minute, for in that time all the liquid neon in its cryostats was converted into gas.

Many other attempts were then made to increase the field by using other cooling agents (e.g. liquid nitrogen and li-

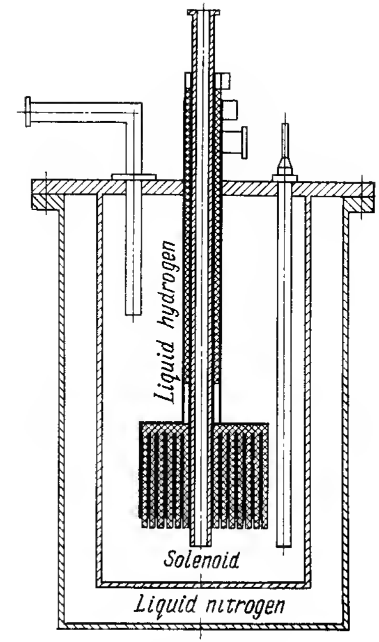

Fig. 14. Current losses can be substantially reduced in solenoids by putting them in a low-temperature medium in which the resistance of the windings is much decreased.

quid hydrogen) and other materials for the coils (e.g. sodium pressed into a thin steel tube). Although the results of these experiments were promising, no one succeeded in producing a stronger field.

These magnets are usually fed from their own power installation generating several thousand kilowatts of direct current. When this power is insufficient (as happened with Kolm's record-breaking solenoid) a fly-wheel is put on the shaft of the machine. By storing sufficient energy in it, it is possible, as Kapitza did many years ago, to draw several times its nominal power from a generator for a short period. At the Royal Radar Establishment in Great Britain

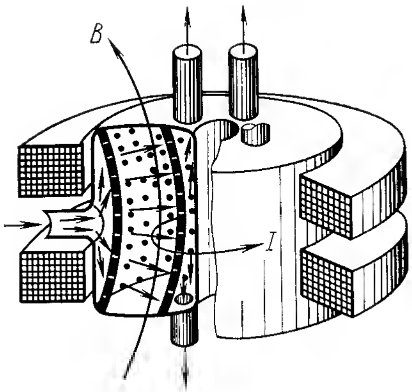

Fig. 15. A magnet that has not yet been built. Kolm's hydromagnet. A stream of liquid silver or sodium would be used as coils.

powerful submarine accumulators were used as the power source for a solenoid.

In the search for new paths, Kolm worked out the design of a solenoid he called a hydromagnet. It consisted of two co-axial tubes, between which a good conducting liquid like liquid sodium or liquid silver was circulated in a radial direction. The two tubes were put into a small magnetic exciting field (Fig. 15). The incoming liquid crossed the lines of force of the exciting field and electromotive force was induced in it. Under the action of the e.m.f. an electric current began to flow in the liquid in the same direction as the current inducing the exciting field. Thus the liquid itself became the solenoid coil. The strength of the magnetic field that can be obtained from this 'coil' depends upon the velocity of the liquid, its electric conductivity, and the strength of the excitating field. Kolm calculated that it would be possible to obtain a magnetic field of 400 000 oersteds in a hydromagnet filled with molten silver at a temperature of 1000°C and a magnetic excitating field of 60 000 oersteds, using 70 megawatts of power and an input velocity of 200 litres per second for the silver.

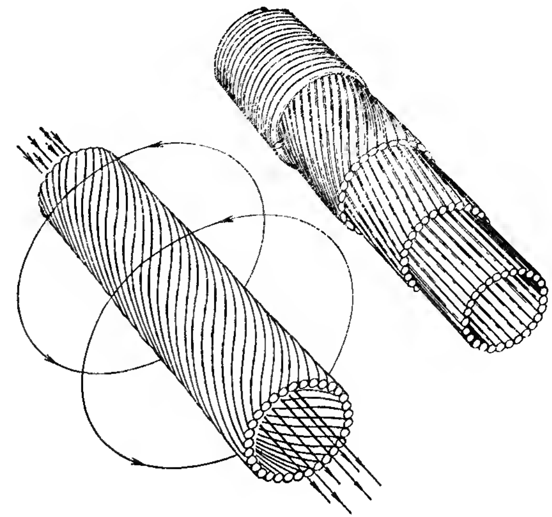

Fig. 16. Coils wound in this way are almost free from the terrible drawback of powerful electromagnets, as the forces generated in the coil by the pressure of the magnetic field are reduced.

Other difficulties apart, however, the material from which the coils are made begins to flow at such enormous fields because of the pressure of the magnetic field. As we have already mentioned, the pressure in Kolm's 220 000 oersted solenoid was three times the pressure at the bottom of ocean deeps. And the pressure increases in proportion to the square of the field. So if we increase the field a little more than three times the pressure increases tenfold.

With a field of one million oersteds the magnetic forces are equivalent to those at the muzzle of a cannon when it is fired. Maintaining it is much the same as trying to fire a gun in such a way that the shell is retained in the breech and not ejected and the gun does not explode.

Is growth of field strength invariably connected with

increase in pressure? Electromagnetic force is always set up because of the vector product of the current density in the coil and the induction of the magnetic field (this is the same Lorentz force that deflects particles in accelerators). The vector product of the two vectors is at its greatest when the direction of the current is at right angles to the direction of the magnetic field and is zero when the directions of the current and of the field coincide. Some scientists have employed this circumstance and designed a configuration of the coils and solenoids in which forces are almost totally absent, and which they have called 'force-free'. A huge 'force-free' system for research into thermonuclear reactions has recently been built that operates on quite a different principle, that of transferring the forces from the solenoid coils into a massive steel base.

From studies of the possibility of building 'force-free' coils Soviet and American scientists have concluded that the problem is by no means hopeless.

Let us consider, for example, a coil built like a long spiral with a large pitch. It would set up two fields (there is, of course, only one field, but for convenience's sake, it is often divided into an axial and a radial part, which together make up the whole field): the total field, which is directed along the axis, and the field that surrounds each separate wire. The axial field tends to split the coil; the field surrounding the coil, on the other hand, tends to compress it. In this way the forces acting on different sides cancel each other out (Fig. 16).

Another coil made in several layers, the inner one almost parallel to the axis and the outer one almost perpendicular to it, would possibly be more acceptable. In it the transition from the axial to the radial field would be gradual and the compressive forces would be spread out evenly over all the layers. This system is the prototype for the powerful systems of the future in which colossal magnetic fields will be combined with elegant design.

PULSED MAGNETIC FIELDS

About a Superweapon that Failed

Being a description of the role of the scale that can be used to measure the enormous strength of the magnetic field obtained by Soviet scientists.

At the end of the nineteenth century an American, Col. King devised a 'superweapon'. He wound telegraph wire around the muzzles of two massive howitzers and switched on a current. The steel barrels of the howitzers were instantly transformed into the cores of an immerse electromagnet. The colonel thought that the field it set up would 'fool' the compasses of enemy ships and either bring them within range of shore batteries or make them run aground.

But the scheme failed and the compasses of ships were not affected. The 'terrible' magnets were too far away from the enemy. But within two metres it was quite impossible to keep anything iron about your person. And on the barrel of the magnet-gun hung five cannon balls, each weighing about 200 kgf. It was rather like a miniature version of the magic magnetic mountain in *The Arabian Nights* that used to pull the nails out of ships. The cannon had a magnetic field of about 500 oersteds.

Other things being equal, the force of a magnetic field is proportional to the square of the strength of the magnetic field. So the field of 25 million oersteds achieved by Soviet scientists bears thinking about. It has a force ten times greater than that at the centre of our planet!

And it does have some useful applications.

That is why the President of the USSR Academy of Sciences M.V. Keldysh touched on this question during his speech at the 23rd Congress of the Communist Party of the Soviet Union in 1966. The award of a Lenin Prize in 1966 to the group of physicists who had theoretically demonstrated the new possibilities of obtaining super-powerful magnetic fields underlined the significance of the problem.

It All Began with an Electric Eel

In which tribute is paid to the 'great bookbinder', a tribute that is more symbolic than real insofar as the first man to open the door to the new field of physics, that of super-powerful magnetic fields, was Prof. P.L. Kapitza, Mem. USSR Acad. Sci.

Pulsed magnetic fields are widely used in modern research and have been since Peter Kapitza began using them in the Twenties.

There is no need to look far to demonstrate the earlier sources from which the experiments probably developed.

In the famous argument between Volta and Galvani it was Volta, we know, who emerged as the victor: the frog legs twitched because of an electromotive force that developed in the artificially created source. It was simply that frogs' legs are a sensitive measuring apparatus. But Galvani was also to a certain extent right. His thesis about the electricity that exists in all living creatures anticipated by two centuries the teaching now familiar to everyone about bioelectricity. All living things without exception have biocurrents. The human heart, for example, creates an electric current on the surface of the body of approximately one-thousandth of a volt, and the brain a current one-tenth of that strength. The giant electric ray can emit a current of some 50 to 60 volts, capable of killing a large

fish. And the electric eel, that dwells in South-American rivers, can develop a potential difference on the surface of its body of 500 volts.

When Volta invented his electrochemical cell he suggested that the electrical organs of the eel worked on a similar principle.

But, as later became clear, the electrical organs of fish are not analogous to a galvanic cell, which can maintain a constant current over a long period of time, but to a condenser, in which more or less lengthy accumulation of charges precedes a powerful discharge.

Electricians have a golden rule: before you write about a new discovery, always read Faraday carefully. Ninety-nine times out of a hundred you find that the 'great bookbinder' had either already made the discovery or else had suggested that work should be done in this direction, or had simply thought about it.

So, before beginning this chapter on pulsed magnetic fields, I also browsed through a brown volume with Faraday's profile stamped on the cover. To my great surprise I found that the first classic experiments on the nature of the electric eel had been made by Michael Faraday. He presented the results to the Royal Society in December 1838. Faraday touched the fish with two metal electrodes, which had copper wires at their other ends. The wires in turn were joined to a small solenoid consisting of a spiral of wire with an iron wire inside it. When the eel discharged a current the solenoid created quite a strong magnetic field, which magnetized the wire. Faraday determined the polarity of the current in the eel from the arrangement of the poles in the wire. The experiment has long remained an exotic episode in the history of physics. Only many years later did Kapitza begin to master pulsed magnetic fields.

Peter Kapitza was born in 1894 in Kronstadt. He graduated from the Petersburg Polytechnical Institute, and in 1921 was sent to England to work under the famous British

physicist Sir Ernest Rutherford, F.R.S., at the Cavendish Laboratory in Cambridge.

Kapitza began working with Rutherford and stayed in Cambridge for about 14 years. His first researches were concerned with nuclear physics, but after a time the young physicist found a completely new field of activity for himself. Initially, he had suggested that a Wilson cloud chamber be put in a magnetic field in order to study the properties of alpha particles. The trajectory of the charged particle was deflected in the magnetic field, the radius of the deflection depending upon the speed of the particle. After completing a series of experiments in fields up to 43 000 oersteds Kapitza decided to extend his measurements into more intense fields. For this he had to build solenoids with a field ten times stronger than anything yet achieved.

The basic difficulties in creating powerful fields were that they required an enormous current and that there was a real danger that the solenoid would be ruined by overheating. He proposed to get around these problems by creating powerful fields for very short periods, which would allow him to make the necessary measurements and at the same time avoid destruction of the solenoid.

Any coil possesses thermal inertia, and it cannot be heated instantly to melting point even by a very heavy current. On the other hand, in systems working briefly, the problem of a powerful source is greatly simplified, as the current is only required for a short time. Therefore devices can be used that give a powerful instantaneous discharge followed by a comparatively prolonged period of recharging.

There are quite a few such systems. It would have been possible, for instance, to use the electric energy accumulated in a condenser battery, discharging, for all intents and purposes, through a short circuit.

It was also possible to utilize the magnetic energy accumulated in a transformer. According to Kapitza's calculations a field of 500 000 oersteds would require a transformer

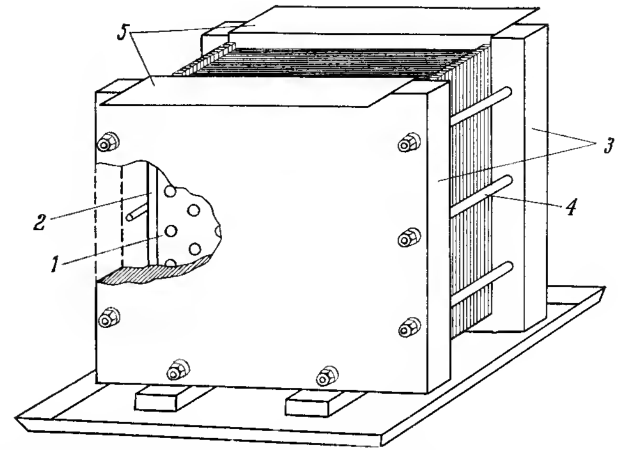

Fig. 17. Kapitza's condenser battery (accumulator) *1*—india-rubber discs; *2*—rubber washers; *3*—solid slate slabs; *4*—bolts; *5*—lead end-plates (35 cm × 35 cm × 1.5 mm) (from the *Proceedings of the Royal Society*).

with a small number of coils on the secondary winding and a core two or three metres long and 30 to 40 centimetres in diameter.

Kapitza made this experiment on a small scale with P.M.S. Blackett. It did not work. It became clear that it was almost impossible to break the transformer's primary winding quickly by mechanical means; at breaking point an arc developed and the energy of the magnetized iron, instead of being brought down in an avalanche to the secondary winding, returned to the primary and was discharged in the arc.

The condensers of the time were also unsuitable because they were very primitive and clumsy.

Kapitza turned to storage batteries of accumulators. They also had to be specially built, as it was essential that their capacitance and active resistance be minimal (Fig. 17).

With his new storage batteries he succeeded, by short-circuiting them, in obtaining a momentary current of 7000 amperes and an instantaneous power of 1000 kilowatts. Discharging the battery on a solenoid with an internal diameter of one millimetre Kapitza got a magnetic field of 0.5×10^6 oersteds for three-thousandths of a second until the solenoid exploded. Experiments were made on all sorts of solenoids with this battery. In one, wound with copper wire, a field of 130 000 oersteds was measured; when it was dipped in liquid nitrogen it proved possible regularly to obtain a field of 250 000 oersteds. This was the largest field they managed to obtain then using batteries. For larger fields it was essential to find another, more powerful source of power. At the same time the source must produce something in the order of 50 000 kilowatts in the time needed to heat the coil to 150°C (the thermal limit of the insulation), which was one-hundredth of a second.

For his source Kapitza used a generator with a nominal rating of 2000 kW, which did not overheat when shorted as normal generators did, and gave 50 000 kW for 0.01 of a second without dangerous consequences. The generator was built by Metropolitan Vickers to the specifications of Kapitza, M.P. Kostenko, and Miles Walker. It was driven by a special electric motor powered by accumulators.

The rotor of the generator weighed 2.5 tons and had a diameter of 50 centimetres. Its large moment of inertia made a special flywheel unnecessary. The generator produced alternating current, which was very essential, since a large short-circuit current was only wanted for a short period of time. If the generator had produced direct current it would have had to be switched off after 0.01 of a second, and that was a very complicated problem. Alternating current, of course, passes twice through zero in each rotation and it does not present special difficulty to switch the generator off as the current approaches zero. They had only to synchronize the moment when the current approached zero accurately with the moment when the generator was short circuited. It is impossible to do it with absolute accuracy: the shorting could coincide with the time when the current in the winding was not yet zero. Just in case Kapitza had to design a switch for a current of 5000 amperes (the strength of the current was 30 000 amperes), opening the circuit for 0.0001 of a second, which in itself was a feat of engineering.

The solenoid that had to take the huge current of the short-circuited generator was made from square copper wire. In later experiments an alloy of copper and cadmium was used instead as it possessed greater durability at heightened electrical resistivity. When the current from the generator passed through the coil immense mechanical forces of tens of tons developed in it; and so that they should not smash the coil it was reinforced on the outside by a strong steel ribbon, which bore the brunt of the pressure.

But that was not all. The powerful forces induced the coil to unwind slightly and its ends to come away from the contacts that fed the current into it; coil after coil was ruined because of this secondary phenomenon, which developed after the basic difficulties seemed to have been overcome. It took several months to overcome this snag. Finally a solution was found. Kapitza made a coil which could 'breathe', or expand automatically; one of the contacts was moveable, and after several tests it took up the position that 'suited it best'.

Another serious obstacle was the shortness of the time for making all the measurements. For the magnetic field in the solenoid lasted for a hundredth of a second and all the experiments had to be begun and completed in that time.

The work was further complicated by the micro-earthquakes that occurred when the generator was sharply braked at the moment the coil was shorted. Although the generator was mounted on a massive foundation, resting on a rock base with a shock-absorbing cushion, the wave of

the micro-earthquake still distorted the measurements. To avoid this Kapitza suggested an extremely elegant solution. He put the solenoid and the object under study at the other end of the hall, 20 metres or so from the generator. The earthquake wave, travelling at the speed of sound in the given medium, took 0.01 of a second to travel the 20 metres and so reached the solenoid when the measurement had already been made.

When a short-circuit current flows through a coil extremely high local temperatures are induced, which gradually even out. It has been calculated that these local temperatures should exceed that of the Sun. Professor Eddington joked that although the temperatures at the centres of the stars might be millions of degrees they were quite cool compared to the Cavendish Laboratory when Kapitza was at work and Rutherford was trying to split the atom.

When Rutherford was in Cairo in 1925 Kapitza wrote to him about his experiments to say that they had obtained a field greater than 270 000 in a cylinder one centimetre in diameter and 4.5 centimetres long. They couldn't go any further because the coil exploded, and did so with a deafening roar that would undoubtedly have given Rutherford great satisfaction if he could have heard it....

But the explosion only caused a great deal of noise, since, apart from the coil, no other apparatus was destroyed. The coil had not been reinforced with an outer rim, so they now intended to remedy that.

Kapitza said he was very happy that everything in general had gone well; and assured Rutherford that 98 per cent of the money had been put to good use and that everything was working properly.

The accident had been the most interesting part of the experiment and finally confirmed their confidence in success, since they now knew for certain what happened when a coil exploded. They also now knew what an arc of 13 000 amperes looked like. The apparatus was apparently in no

particular danger, nor the experimenter, providing he stood far enough away.

Kapitza concluded that he was very anxious to see Rutherford again in the laboratory so that he could give him all the details, some of which were very funny, about their skirmish with the machines.

Using a pulsed generator Kapitza managed to do systematic research in magnetic fields up to 320 000 oersteds. This field, occupying a volume of only two cubic centimetres, became the upper reliable limit. Kapitza, jointly with other scientists, investigated Zeeman and Paschen-Back spectra, magnetic resistance, magnetostriction, and other phenomena up to this limit.

In one of his articles reviewing the possibilities of obtaining even stronger fields, he pointed out that even at that time (in the Twenties) technology was sufficiently advanced to build condensers able to give a pulse of two or three million oersteds.

The technical obstacles, however, proved so great that only now, forty years later, have we succeeded in obtaining the fields about which Kapitza spoke. The record he established stood for more than twenty years and was not broken until the Fifties.

Magnets and Explosions

In which we describe how the most intense magnetic field ever at man's disposal was obtained.

Groups of physicists in the USA and the USSR became concerned with the problem of obtaining intense magnetic fields through the need to study the properties of elementary particles in thick photographic emulsions. For example, physicists at Harvard University's cyclotron laboratory wanted to get a field that would noticeably deflect the

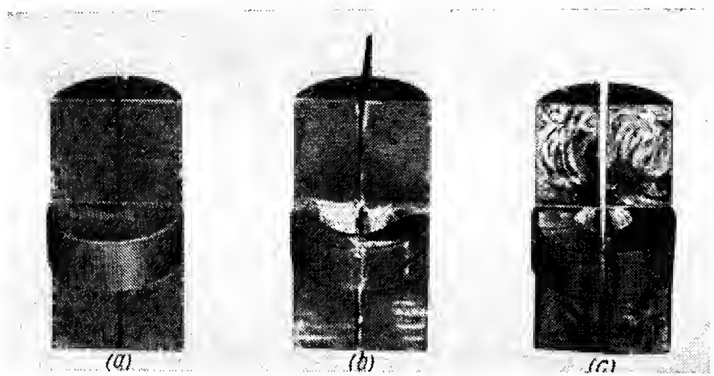

Fig. 18. Turns for developing pulsed magnetic fields of (*a*) 800 000 oersteds; one million (*b*) and (*c*) 1 600 000 oersteds.

trajectory of particles entering emulsion. The needed field would have to be more than 200 000 oersteds.

The problem of obtaining such fields proved so complex and interesting that the physicists became far more involved in it than the finding of a method for treating photo-emulsion, which had been the original stimulus, would have dictated.

Results were soon obtained that exceeded all expectations. Using powerful batteries that could produce one million kilowatts in 0.00001 second (the famous Dnieper Dam only produced 600 000 kW), they got a field of over one million oersteds. The sudden release of such vast energy was accompanied with a bang like a clap of thunder.

The whole avalanche of power was driven into one solitary, massive coil (Fig. 18). As Kapitza had shown, a normal solenoid, wound with copper wire, was good only for fields up to 300 000-350 000 oersteds. Bitter solenoids, made of copper discs, are stronger, but even they cannot

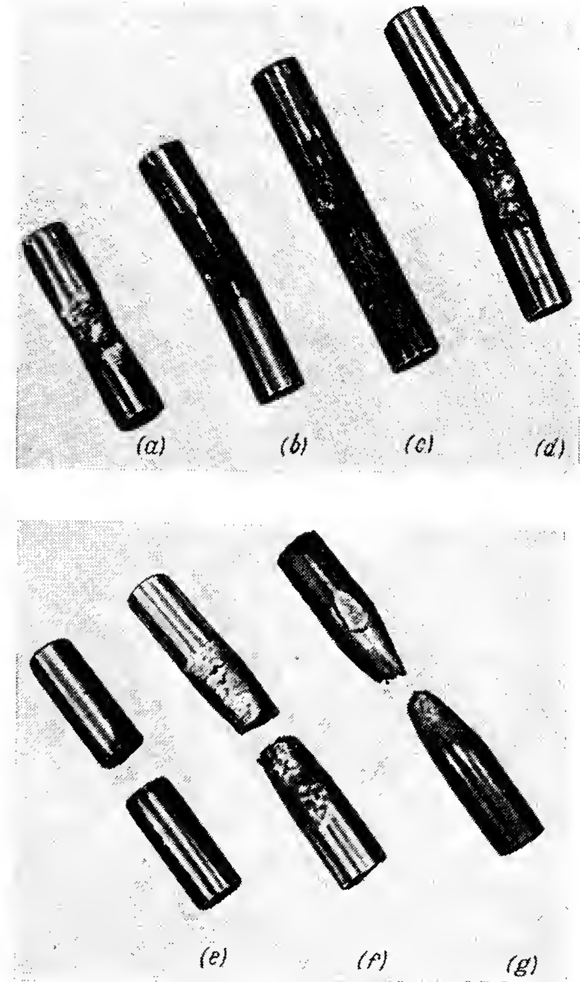

Fig. 19. Examples of various metals that have been in a pulsed magnetic field of 600 000 oersteds: (*a*) copper, (*b*) steel, (*c*) special steel, (*d*) brass, (*e*) tungsten, (*f*) silver-plated brass, (*g*) aluminium.

withstand fields between 500 000 and 700 000 oersteds. Solenoids are unable to counteract the huge forces set up by such fields. The insulation between the turns is an especially weak point; to get over this drawback it is necessary to use a single massive turn and holder made of copper, tempered steel, or beryllium bronze.

The aim of experiments became primarily to discover how far metals could withstand the mechanical and thermal consequences of very intense pulsed fields (Fig. 19). It was found that no metal could support the forces set up in a field of a million oersteds and it began to look as though the progress made with intense fields would be limited by this figure. But physicists now seem to have found a way out of this difficulty, too, by using the 'force-free' windings we discussed earlier.

A large number of 'force-free' and low-power windings have been devised. Until such times as more durable and refractory materials are discovered 'force-free' coils are physicists' last hope of obtaining stable strong fields in indestructible coils.

It is now common for fields between 200 000 and 700 000 oersteds to be obtained by discharging powerful condenser banks onto a Bitter solenoid sometimes reinforced with ceramic for strength or onto a single turn. In the Soviet Union, there are such installations at Moscow University, the Physics Institute of the USSR Academy of Sciences, and in Sverdlovsk, and other centres.

But was there no other way of obtaining intense fields than suddenly bombarding a solenoid with vast energy? In 1940 the Soviet electrical engineers G. Babat and M. Lozinsky published a paper in which the idea of a flux 'concentrator' was mentioned for the first time.

The idea is fairly easily understood. Imagine a slotted cylinder carrying current, closed at the slotted end by a metal piston. The current sets up a magnetic field inside the cylinder, the strength of which is characterized by the

density of the magnetic lines of force, i.e. how many there are per unit of area of the internal cross-section of the cylinder. When the piston is suddenly driven into the cylinder the cross-section of the latter is sharply reduced. And because the number of the lines of force concentrated in the tube cannot be instantly altered, their density in the reduced section increases just as sharply. Consequently, the magnetic induction and intensity of the magnetic field also increase.

So the principle of flux concentration is that first a comparatively small field is set up in a large volume by normal methods and then the cross-section of the magnetic flux is somehow made very much smaller so that the field increases sharply.

If the wires of the winding were superconductors, the expanding field could be maintained for as long as convenient. In normal conductors induction currents quickly die away and the field lasts for only a fraction of a second.

Using Babat and Lozinsky's idea, Howland and Foner made a concentrator in which there was no mechanical reduction of the working area of the magnet. It was found that, by putting a massive coil of small internal diameter into the solenoid, it is also possible to achieve a concentration effect. With a pulse of current in the outer winding, the eddy currents are set up in the massive coil, which force the magnetic flux to the bore of the coil. With the help of the concentrators they obtained a field of 450 000 oersteds, where a solenoid without a massive coil would have had a field of only 350 000 oersteds.

In other experiments they succeeded in obtaining a field of 200 000 oersteds in a quite large volume, approximately that of a tumbler. In this space they placed thick photo-emulsions to investigate nuclear processes. The battery of condensers weighed more than 30 tons.

The high point of all this research into super-powerful magnetic fields was the series of experiments made some

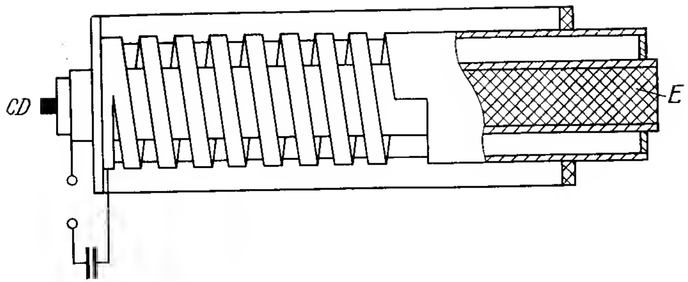

Fig. 20. The principle of the MC-2 magnetocumulative generator (which employs a charge of TNT to compress the part containing the magnetic flux); CD, detonator capsule; E, explosive.

years ago by Soviet physicists R.Z. Lyudaev, E.A. Feoktistova, G.A. Tsirkov and A.A. Chvileva under the guidance of A.D. Sakharov. Examining the idea of concentration of the magnetic flux and realizing that its effectiveness, increased with the speed at which the zone of concentration is 'collapsed', they concluded that the effect would be optimum if it were produced by means of explosives. For when a field is set up within a massive closed coil and the coil is then compressed by a cumulative explosion, the density of the lines of force and, consequently, the strength of the magnetic field inside the contracted coil are greatly increased, because the magnetic flux within its contours cannot instantly change.

Similar ideas were tried out by American physicists at the Los Alamos Laboratory. The principle of the device used in the Soviet experiments is shown in Fig. 20. An initial magnetic field of one million oersteds has been obtained with apparatus employing an explosion.

The metal ring, 7.5-10 cm in diameter, holds four to eight kilograms of explosives. When the outer field reaches its maximum the explosives are fired and the diameter of

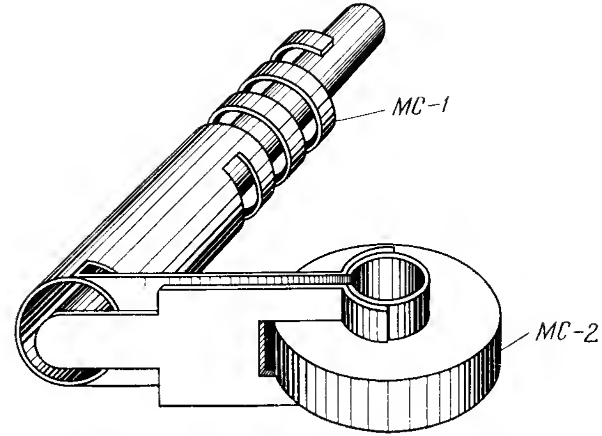

Fig. 21. The assembly of MC-1 and MC-2 magnetocumulative generators used to obtain a record magnetic field of 25 million oersteds.

the ring is compressed several millimetres at a rate of 'collapse' around 0.5 cm in 0.000001 second (5 km/s).

The Soviet physicists recorded the incredible field of 25 million oersteds* and the Americans a field of 18 million oersteds. Further measurements of the field were impossible as during 'collapse' the diameter of the ring decreased so much that it crushed the sensor that was taking them. The whole process took only a few millionths of a second.

Many eminent scientists think that the field obtained is not the limit and that fields of 100 million oersteds and

* The record field was obtained by consecutive use of two explosive or magnetocumulative generators—MC-1 and MC-2. The second generator was used to create a 'spark' field that then collapsed the MC-2 generator. The arrangement of these two unique pieces of equipment is shown in Fig. 21.

Fig. 22. Apparatus for stamping metal details by means of magnetic pulses.

higher could be obtained in the same way. Such unimaginable fields exist only in the depths of planets and stars. Since the pressure of a magnetic fields increases in proportion to the square of its intensity, such immense fields would develop corresponding pressures (thousands of million atmospheres).

The carrying out of experiments that simultaneously combine such enormous fields and pressures is of inestimable value, for example, for studying the processes taking place within planets and stars, during the gravitational collapse of superstars, and so on.

Have pulsed fields any application in engineering? They have, and although their technological use is still only in its infancy, its future is extremely promising.

A pulsed magnetic field is used, for example, to clench a protective metal covering on steel cable. The pressure from the field is so great that the covering is pressed against the uneven surface of the cable tighter than is possible in any other way.

The electromagnetic forces set up in powerful magnetic fields can be used in exactly the same way to stamp out details, to press leads into insulating bushes, and for other technical purposes (Fig. 22).

It also looks as if super-powerful magnetic fields will find application in long-range space radio communications, and in the study of elementary particles and the properties of plasma.

Possibly the most grandiose and daring plan for exploiting pulsed fields in physics research was the one devised by Sakharov. He suggested using a large magnetocumulative generator to obtain charged particles of a colossal energy. To impart an energy of 10^{12} electron volts to particles, it would be necessary to use an atomic charge. The proposition was to make an explosion in a chamber with a volume of 10 000 cubic metres at the bottom of a 1000-metre shaft. Surprisingly enough such an apparently extremely expensive arrangement would be considerably cheaper than a conventional accelerator giving particles of equivalent energy.

THE MAGNETIC SYSTEMS IN ACCELERATORS

Powerful Magnets in Modern Science

In which we tell about the most powerful magnets built by man, giant steel wonders between whose polished poles, atomic particles, so tiny that it is difficult even to imagine them, whirl in a dizzy waltz.

The first cyclotron was built by E.O. Lawrence in 1932 at a cost of 1000 dollars. The American 6000-MeV synchrotron already cost 30 000 dollars, while the Brookhaven synchrotron (30 000 MeV) cost an enormous sum of 34 000 000 dollars. The 76-GeV Serpukhov accelerator cost 400 million roubles. The larger accelerators are even more expensive. More than half the cost goes on making their enormous magnets, the largest and most expensive magnets in the world and necessary elements in most charged particle accelerators. And although their magnetic fields do not exceed 15 000-17 000 oersteds accelerators are far and away the largest machines used in physical investigations and engineering.

Accelerators were built for two basic purposes: first to discover new particles and second for research into the structure of the objects of the microworld (i.e. of these particles).

Previously unknown particles could be obtained in an accelerator through the interaction of accelerated particles and the nuclei of various elements. Study of the minutest structures in the microworld in accelerator was based on the fact that a flux of accelerated particles, in accordance

with the laws of quantum mechanics, can be represented as waves of a definite length. The higher the energy of the particle, the shorter is the length of the wave. We know from physics that we can only see objects whose linear dimensions exceed the length of the wave (light waves are relatively long so that the possibilities of seeing tiny objects through an ordinary microscope are very limited).

A particle accelerated to the maximum has the shortest possible wave and is therefore suitable for studying the super-small objects of the microworld.

To resolve the problems connected with research into the structure of space (whether the structure of space possesses quantum properties within the range of distances of 10^{-15} cm and less) and also the structure of time (it may be that time does not flow continuously but in bursts at intervals equal to or shorter than 10^{-25} of a second!) particle accelerators with energies up to a million MeV are needed. That is almost a million times more energy than Lawrence obtained in 1932. Such accelerators will need ring magnets with a diameter of three to five kilometres.

Scientists hope to find answers to many questions with the aid of powerful new accelerators. Why, for example, did nature choose hydrogen as the element for synthetizing all the others? Why is a proton exactly 1836 times heavier than an electron? Is there any connection between electromagnetic and gravitational phenomena, and between these and other 'strong' and 'weak' nuclear interactions? Is there a fifth force in nature other than the four? Could a 'fifth force' explain the non-conservation of parity in some nuclear reactions? Are there such things as monopoles in nature, particles with only one magnetic pole, equivalent to electric charges?

Finally, are there 'quarks', from which all elementary particles, possibly, are composed?

So it is necessary to keep on increasing the energy of particles. How can it be done?

In a book by E.G. Komar, one of the best-known builders of the big Soviet accelerators, there is an interesting list of the various ways of accelerating matter.* When we say we accelerate a particle or impart energy to it, what exactly do we mean? We mean we increase its speed. When we throw a stone, we accelerate the charged particles that make up its atoms. Particles may be accelerated by other means, too, for example by firing them from a gun.

Let us look at what happens when we fire them. Say the bullet weighs 100 grams and flies at a speed of one kilometre per second. Its kinetic energy can be expressed by this formula:

$$E = \frac{mv^2}{2} = \frac{100 \times 10^{10}}{2} \text{ erg} = 3.13 \times 10^{17} \text{ MeV}$$

Shooting would seem to be the ideal method for accelerating particles, as, with little expenditure, we obtain energy far in excess of what even the more 'shameless' physicists have dreamt of. But it is not quite as simple as that. This colossal energy is distributed between the particles, and the energy of each particle taken separately, which determines the intensity of the nuclear transformations, will of course be insignificant. Each proton in the system would acquire only 0.005 eV, which is quite inadequate.

Can the speed of the bullet be increased? In the energy formula it is the squared term and strongly affects the rate of acceleration. It has been calculated, however, that even if the bullet reached cosmic speeds the energy of the elementary particles would still be insufficient.

Could the idea that underlies all electrical motors perhaps be used for accelerating particles? Suppose we had a very long electromagnet—of the order of several kilometres, with a field in the gap of about 20 000 oersteds. If a conductor were then placed in the gap the conductor would begin to move; and when it had finished moving it would have acquired considerable energy, providing, of course, it had not melted. The higher the acceleration we want to achieve the greater the current in the conductor has to be. Fusion occurs in ordinary conductors at a velocity of 10^7 cm/s, which is clearly inadequate for accelerating to high energies.

Hopes for realizing this method were revived in 1961 after the discovery of superconductors that did not lose their zero resistance in strong magnetic fields (of more than 100 000 oersteds) when a current of high density (above 1000 A/mm²) passed through them. In the movement of the superconductor with a current density j along directing rails in a magnetic field H the force acting on 1.0 cubic centimetre of the substance is

$$p = 0.1\, Hj \text{ dynes}$$

The acceleration caused by this force is

$$a = \frac{p}{\gamma} = \frac{0.1\, Hj}{\gamma} \text{ cm/s}^2$$

where γ is the density of the superconductor in g/cm³.

If $H=10^5$ oersteds, $j=10^5$ A/cm², and $\gamma=7$ g/cm³, the acceleration will be

$$a = \frac{0.1 \times 10^5 \times 10^5}{7} = 1.4 \times 10^8 \text{ cm/s}^2$$

and the length of the accelerator will be

$$l = \frac{v^2}{2a}$$

If we want to obtain a velocity of 10^7 cm/s the accelerator will have to be 36 kilometres long. Even using superconductors the dimensions of the magnetic system for comparatively small velocities prove to be extremely large.

The most effective method is to accelerate charged particles in an electric field. Under the influence of a potential

* E.G. Komar. *Uskoriteli zaryazhennykh chastits (Charged Particle Accelerators).* Moscow, 1964.

difference of one million volts an electron acquires an energy of 1 MeV. Since modern technology can operate quite freely with voltages of the order of five million to ten million volts, obviously this method has no equal.

But multiple acceleration, in which the particle repeatedly passes through the same 'accelerating gap' in which the potential difference is between 100 000 and 400 000 volts, is more commonly used. This method was proposed by Lawrence, who used a magnetic field to return particles to the accelerating gap, as it was known that any charged particle moved in a circular fashion in a magnetic field. Lawrence placed accelerating gaps at two places on the circle.

As the energy of the particles obtained in accelerators rises, so the radius of their orbits increases and with it the diameter of the magnets, which is why the biggest magnets in the world are those in accelerators.

A charged particle is subjected to two forces in a cyclotron: centrifugal force, which tends to eject it from the cyclotron, and centripetal or Lorentz force that impels it to move around the circle.

Centrifugal force, as we know, is expressed by the following equation:

$$P_c = \frac{mv^2}{r}$$

where m is the mass of the particle, v is its velocity, and r is the radius of the orbit.

The Lorentz force can be expressed by the equation

$$P_H = 0.1\, eZHv$$

where eZ is the charge of the particle, and H is the strength of the magnetic field.

These equations show that the magnetic field in a cyclotron must be uniform, that is to say, it must be consistent in size and strength along the whole of the orbit. If, for

example, it dropped sharply to zero at some point of the orbit the particle would not be held by the centripetal force at that point and would shoot out of the cyclotron.

So it follows that the intensity of the field along the orbit of a cyclotron must be absolutely constant.

The equality of the centrifugal and centripetal forces in the equilibrium orbit ensures what is called the 'horizontal stability' of the particle. What exactly does that mean?

Let us suppose that a particle passes from the equilibrium orbit to a larger one under the influence of some force or another. The centripetal force will then be greater than the centrifugal force and as a result the particle will be thrown toward an orbit of shorter radius until it once more achieves an orbit of equilibrium.

As the radius of the orbit shortens an opposite picture is observed.

But what happens if the particle crosses to a lower or a higher orbit? If the pole pieces of the magnet are parallel to each other and the magnetic lines of force, which should be perpendicular to its steel surfaces, are parallel and straight, then the magnetic field will remain constant whether the particle takes a higher or lower orbit. All orbits—high, low or medium—will be all the same to the particles, which will lead (because of the unideal state of the surfaces of the poles) to their becoming 'lost' in the poles of the magnet.

To prevent that from happening or, as they say, to maintain the 'vertical stability' of the particle's movement, the poles of the magnet are beveled so that the distance to their edges is increased.

In fact, however, it is not the poles that are beveled but the magnetic sides of the vacuum chamber in which acceleration takes place.

In this case the magnetic field of the accelerator is altered: the lines of force directly under the centre of the pole will still be straight, perpendicular to the plane of

the poles, but those at the outside of the pole will be bent outward, giving them a 'barrel-shaped bulge'. Around the 'equator' of the 'barrel' the field is minimal, but increases on either side of it. A particle moving in such a field cannot hit one of the poles because it would have to cross over from an area with a weak field to one with a strong field and thus expend a certain amount of energy.

The poles themselves are conical so that the magnetic lines of force of the dispersion flux diverge from them along their height. Thus the further the flux passes along the poles from the working zone, the more intense it is.

What would happen if the pole were cylindrical and its cross-section constant in height? The induction in the pole near the working zone in that case would be very low ($B=\Phi/S$, Φ being the magnetic flux and S the cross-section of its path) and extremely high far from the working zone. The poles would be loaded differently in various sections and (and this is the main point) irrationally. To prevent that they must be conical. The smaller section will then correspond to the smaller current, induction will be the same in all sections, and the pole will be evenly loaded.

The scientists ebdeavour to get the induction in the pole equal to that in the working zone, i.e. 14 000-17 000 gauss. Why didn't they take a higher induction? In principle they could have but at higher levels the magnetic core is strongly 'saturated', so that it requires a large magnetizing current to induce a magnetic flux along it. Besides which, if the poles are saturated, it is difficult to ensure the required distribution of the magnetic field in the working zone.

The conical poles for the electromagnet of a cyclotron are generally made from a single steel forging.

The main coils, usually made of copper or aluminium busbar, with a cross-section of 50-100 mm² and an opening inside, through which cooling water is circulated, are fastened to poles, creating a strong magnetic field.

In addition to the main winding, cyclotrons have a supplementary one near the gap, usually made from two coils placed near the edge of the pole. They 'aim' the particles at the target, in other words they regulate the height of the plane along which the particles move in the cyclotron.

Because of various accidental factors this plane is not usually, contrary to expectations, in the middle between the poles. Anything nearby, a safe, or a steel door, or a gas cylinder, can displace the median plane.

One of the biggest electromagnets of the 'armoured' type already described was built for the 660-MeV synchrocyclotron at the Joint Institute for Nuclear Research in Dubna. It has pole pieces six metres in diameter and weighs 7000 tons. The synchrocyclotron at Berkeley, California, is rather smaller.

The weight of cyclotron magnets can be calculated from the following formula:

$$G = 4.8 \times 10^{-3} r^{2.5} \text{ tons}$$

where r is the radius of the pole in centimetres.

The weight of conventional accelerator magnets is measured in thousands of tons. The magnets are enormous and expensive, and so, consequently, are the cyclotrons themselves. They are normally housed in special buildings surrounded by concrete walls several metres thick, which serve as protection against radiation.

Cyclotrons are mainly used for research. But in recent years they have also been used to produce radioactive isotopes for industry and agriculture. In several countries there are cyclotrons that simply serve as technological equipment for producing isotopes and not for research.

There proves to be an upper limit to the energy of the particles accelerated in a cyclotron. It is imposed by the theory of relativity. The mass of any particle increases as its velocity approaches the speed of light. So a particle of large mass is less 'agile' and begins to lag behind particles

of less energy and to reach the accelerating gap later, i.e., it arrives at a moment when the accelerating electric field is small or is directed against the particle.

It has been calculated that the upper limit of proton energy achievable in a conventional cyclotron is 25 MeV. The greater the intensity of the magnetic field the more revolutions a charged particle makes per unit of time. The question therefore arises whether it is possible to increase the magnetic field from the centre of the pole pieces to their ends. Then the increase in mass, and consequently in the 'inagility' of the particle as its energy increases would be compensated, and the energy of the particles obtainable in a cyclotron increased.

But a cyclotron works the other way round. The magnetic field falls off toward the edge of the pole, causing 'vertical focusing'. How can these opposing demands be reconciled? How could they simultaneously get vertical focusing and build-up of the field from the centre of the pole toward the edge?

The problem had interested people for a long time. Back in 1938 the American, L. H. Thomas, suggested a formula for modulating the magnetic field at the gap or aperture of an isochronous cyclotron, which provided both these conditions at the same time. But the shape of the pole proved too complicated, so the idea of an isochronous cyclotron did not find much support then.

Later the position changed. Instead of Thomas's complicated poles engineers suggested conventional cylindrical poles covered with steel plates of simple shape. The plates ensured both build-up of the field outward along the radius and vertical focusing. Normally a complex system of concentric and sectional correcting coils and plates is used to modulate the field in the aperture (Fig. 23).

Isochronous cyclotrons permit the energy of the particles obtained to be raised to 700 or 800 MeV. Any further increase is problematical because, for technological reasons,

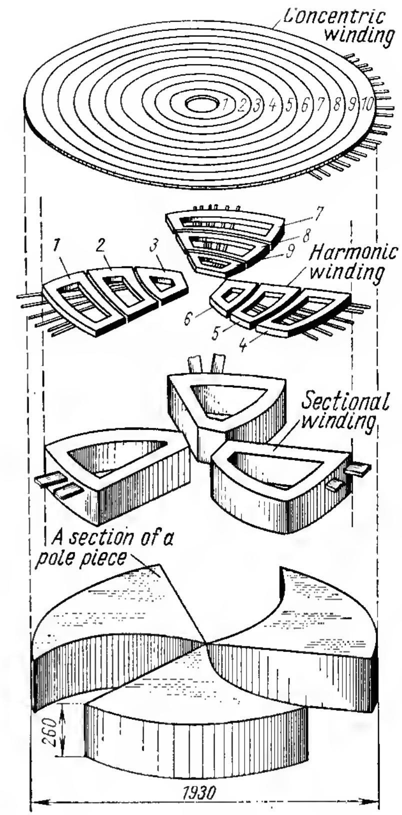

Fig. 23. The supplementary plates and coils that transform a cyclotron into an 'isochronous cyclotron' and increase the energy of accelerated particles twenty-fold.

it is difficult exactly to meet all the requirements as regards the configuration of the magnetic field at such high energies (Fig. 24).

Magnetic systems of the cyclotron type are also used in another type of accelerator, known as a synchrocyclotron, or phasotron, which differs from the cyclotron in the fre-

Fig. 24. This refined shape of the poles helps increase the energy of the particles obtained in a cyclotron.

quency of the accelerating voltage decreasing as the energy of the particles rises, so allowing the particles that are gaining in mass to cross the accelerating gap in time. This change in frequency is equivalent to the change in the field in an isochronous cyclotron. The upper limit of particle energy obtainable in synchrocyclotrons also tends to be 700 to 800 MeV.

Cyclotron magnets have also been installed in the microtrons used for resonance acceleration of electrons in an electric field at microwave frequencies. Microtron magnets usually have small induction, approximately a tenth of that used in cyclotrons.

For various reasons of a theoretical and technical nature, some of which we have already mentioned, it is impossible to build conventional cyclotrons with energies higher than 25 MeV, and isochronous cyclotrons and synchrocyclotrons with energies higher than 800 MeV. But there are also economic factors that limit the building of super-powerful accelerators.

Let us figure, for example, how much a cyclical accelerator with an energy of 10 000 MeV (or 10 GeV) would weigh. If the magnetic field on the final orbit is to be 14 500 oersteds then its radius must be around 25 metres. Substituting that radius in the equation we had earlier for the weight of a magnet

$$G = 4.8 \times 10^{-3} r^{2.5} \text{ tons}$$

we get a magnet weighing 1 500 000 tons. It would be pointless even to consider building it.

Why do high-energy cyclotrons weigh so much? One reason, apparently, is that we have chosen a magnetic field of low strength. If we could increase it several times the radius would be reduced by a corresponding amount and the weight of the magnet by 2.5 times that amount. But the magnetic fields in cyclotrons cannot be significantly increased because the steel would become magnetically saturated.

Another reason is the very principle on which a cyclotron works. Since its magnetic field is constant in time, a particle acquiring a definite 'dollop' of energy in the accelerating gap begins to move along a wider orbit, so that its trajectory resembles a spiral. And it is this spiraling of the orbit that makes it necessary for a cyclotron to have a full set of radii from zero to that of the final orbit. In other words the pole has to be cylindrical, that is to say massive and heavy.

Apparently, however, it is not absolutely essential to have a full set of orbits of varying radii. If the magnetic field in the accelerator altered as the particle's energy rose, as stated in the formula

$$r = \frac{mv}{H}$$

then the radius of the orbit could remain constant. And that only requires ensuring that the rate of change in the

magnetic field approximates the rate of change in the particle's energy.

In that event it would be possible to leave a narrow ring at the edge of the pole instead of having cylindrical poles, and to do away with the core of the pole altogether. It is only accelerators like that that now enable us to obtain beams of high energy particles at relatively low cost (in comparison with a hypothetical cyclotron of the same energy). These ring-shaped accelerators, as they are called, include synchrotrons and synchrophasotrons, the largest and most expensive bits of equipment physicists have ever had at their disposal. Their magnetic system usually consists of several sectional magnets set out in a circle separated by the accelerating gaps. The cost of the magnets for either type (there is little difference between them) amounts to around half the cost of the complete installation, which is hardly surprising when you consider that the ring of magnets has a diameter of tens, if not hundreds of metres.

Vertical focusing operates in synchrotrons on the same principle as in cyclotrons; the magnets are so set up that the magnetic field on their outer radius is less than on the inner one. Thus every particle leaving the median plane experiences a force from the barrel-shaped field impelling it to return, a principle that is called 'weak' focusing.

Table 1

Data on Selected Existing Synchrotrons

Place	Beam energy, in GeV	Radius of orbit, in metres
Batavia	200	1000.0
Serpukhov	76	236.0
Brookhaven	33	128.5
Geneva (CERN)	27	100.0
Dubna	10	28.0

In synchrotrons of this type an energy of up to around 15 000 MeV can be obtained. As we write, the machine at Dubna, that yields particles with an energy of 10 GeV and has a magnet weighing 36 000 tons, is the largest of its type in the world.

Higher energies cannot be obtained using weak focusing because the accelerator radius has to increase with the energy of the particles. The increase in the radius can be calculated from the following formula:

$$E = 300\,Hr$$

where E is the energy in electron volts; H is the strength of the magnetic field in oersteds, and r is the radius in centimetres.

The larger the radius, however, the higher the oscillations of the particle around its stable orbit. Chance molecules of gas in the vacuum tube or fluctuations in the accelerating voltage and frequency can knock the particle out of its orbit. It is therefore necessary to increase the working zone (the aperture of the beam) so that the particle does not get lost in the metal of the magnet while making its roughly 500 000-kilometre journey in the accelerator; and that is extremely expensive—a weak focusing accelerator of 30 GeV would weigh 100 000 tons. To minimize oscillation around particles' stable orbits and to reduce the cross-section of the beam, stronger focusing would have to be introduced, in order as far as possible to prevent particles from moving out of their stable orbits.

Up to 1951 no one knew how to do that. A solution to the problem was suggested by the Brookhaven group consisting of E.D. Courant, M.S. Livingston, and W.G. Schneider. Livingston proposed calculating how a particle would behave if accelerated in a system of several magnets, if the direction of field reduction was altered in each successive magnet. An electronic computer showed that the particle would travel along a stable orbit and in addition would

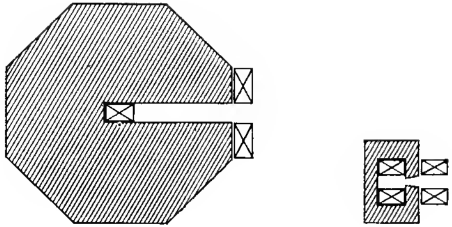

Fig. 25. The comparative sizes of accelerator magnets with (*a*) weak and (*b*) strong focusing.

be subjected to strong focusing forces. In the sector where the pole turned inward there was strong vertical focusing and horizontal defocusing; in the next sector, where the pole turned outward, focusing was the other way round. To the surprise of the Brookhaven group the total effect was that, with a definite arrangement of the sectors, the beam was strongly focused and the deflection of particles from the stable orbit was very small. The effect of the magnets was equivalent in a way to that of two lenses—concave and convex placed one after the other—i.e. of collecting rays.

It proved a very fruitful idea and was used for the Brookhaven and CERN accelerators, which have energies of the order of 30 GeV. A very valuable result was obtained in the Brookhaven machine, the first successful detection of an antideuteron—an atom of antimatter and not just an elementary antiparticle.

The 76-GeV proton accelerator commissioned a few years ago in Serpukhov works on the principle of strong focusing. After visiting it a Soviet popularizer of science said: 'The architect's pen is no longer adequate to describe the Serpukhov synchrophasotron, the world's largest, operating at 76 thousand million electron volts. One needs the landscape artist's brush.

'Imagine something of the order of a geological formation, the panorama, for instance, of a lunar crater big enough to be noted on their maps by modern selenographers. The crater is neither empty nor uninhabited, but populated and covered with grass, and lies in the attractive surroundings of a Russian forest. Our Volga car runs around the foot of it just like an ant on a bicycle tyre. On the very brow of the crater and near it are buildings of concrete and steel. These imposing, quite unique buildings house the separate parts of the accelerator and its various services.

'The apparent lightness of the architecture hides what is a veritable fortress. It has walls, ceilings, and gates of such fabulous strength that even the most arrogant builders of mediaeval castles would bow to. The fortified appearance of king Atom's palaces is a necessary precaution against radiation. The circular tumulus reminiscent of a lunar crater is also defensive, protection against lethal radiation. For the first time physical apparatus, a proton accelerator, almost three times as powerful as its European and Transatlantic fellows, has achieved the size of a small town or a big industrial works.'

To provide strong focusing in the Serpukhov accelerator and similar machines magnet sections in which the field decays in opposite directions are set up one behind the other; when the field in the first magnet falls off toward the outside radius (vertical focusing) it is reduced toward the centre of the next, reducing the horizontal cross-section of the beam. As a result, the cross-section of the beam and consequently the dimensions of the working zone of the magnet are smaller, which enables the energy of particles to be increased without any substantial increase in the weight of the magnet.

The principle of strong focusing soon began to be used in other things than accelerators. Rotary magnets and quadruple lenses working on this principle are widely used, for example, to focus beams and feed them to the experimenter's table.

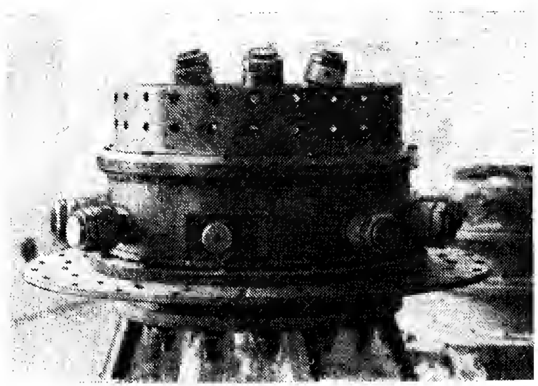

Fig. 26. The most powerful solenoid in the USSR. A constant magnetic field of 200 000 oersteds can be obtained.

The building of accelerators with strong focusing permitted higher energies to be obtained with lighter magnetic systems. But the building of a synchrotron of say 300 GeV needs the economic resources of powerful states. The problem of building one has to be decided at government level, like the building of a new town. The comparison with a town is a very apt one, as a scientific centre with a whole township of scientists and technicians develops rapidly around every large accelerator.

Of course the cost of larger accelerators is considerably higher. A 1000-GeV accelerator would cost around 1000 million roubles. Its sectional ring magnet would be about seven kilometres across. Its construction would involve thousands of people and hundreds of organizations. True, by using strong focusing the magnet required would be kept down to a mere 30 000 tons. For protection against radiation a concrete wall twelve metres thick would have to be built around the accelerator.

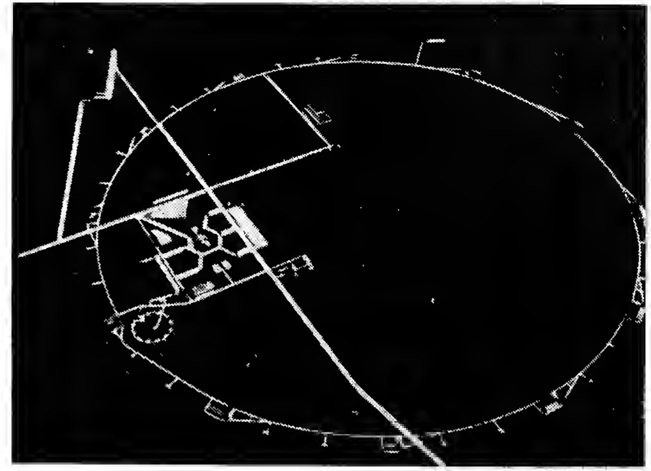

Fig. 27. A model of a 300-GeV synchrophasotron. The magnet would be 2.4 kilometres in diameter.

So the building of such an accelerator is a definite strain even for countries like the USA and the USSR. The strain is 'mental' as well as financial. In one way or another it would involve some 2000 highly qualified professors, a whole army of scientific workers. Therefore the press in some countries often argues that such high-energy accelerators should be built as a joint venture by all developed countries, the USA, the USSR, and the other countries of Europe.

At the conference on high-energy accelerators held in Dubna in 1963 American and West-European scientists produced plans for strong-focusing accelerators of 150 and 300 GeV, and Soviet scientists for 500 and 1000 GeV. But such energies raise new difficulties as regards focusing. The diameter of a 1000-GeV accelerator would be around seven

kilometres, and so that the particle would not deviate from the stable orbit or become lost in the poles of the magnet, the magnet would have to be accurate to one-tenth of a millimetre. The magnetic systems of these gigantic accelerators function on cybernetic principle. Any error in the change of a direction of a beam is immediately registered by instruments and commands are sent to the accelerating system from the computing centre to change its parameters so as to bring the errant beam back to its orbit.

It has still not been decided whether such accelerators will be built separately by various states, or by groups of states, or by the 'whole world'. Is it not possible that physicists will find a more elegant solution that will enable us to obtain colossal new energies at comparatively low cost?

Not so long ago, for example, quite new ideas for building super-powerful accelerators have been advanced. One is that the nucleus and the target, i.e. the particle and the target, should be 'shot' at each other by relatively small accelerators so that they meet and smash into each other with immense, unprecedented force.

Among those awarded the Lenin Prize in 1967 were the Novosibirsk scientists G.I. Budker, A.A. Naumov, A.N. Skrinsky, V.A. Sidorov, and V.S. Panasyuk. They were the first to successfully implement the idea of colliding beams of electrons and positrons. With their VEPP-2 machine, with magnets only three metres across they obtained energy equal to 2000 GeV from the interaction of particles. Not every country in Europe could house a conventional linear accelerator of such power.

The idea of using an accelerator without magnets belongs to Enrico Fermi. He, of course, had in mind an accelerator without magnets, but not without a magnetic field; otherwise the machine would need to be immensely long. Fermi suggested utilizing the Earth's magnetic field, instead of magnets, by employing an accelerator of the synchrotron

type consisting of a vacuum tube encircling the globe along the magnetic equator. Although realization of the project would produce beams of particles of immensely high energy, its cost would obviously be enormous. Furthermore, the particles' orbit must be circular, and the Earth is far from an ideal sphere. To guarantee an ideal circle it would be necessary to blast tunnels through mountains and build viaducts over the oceans, and so on. And there would be the problem of how to ensure that apparatus encircling the Earth would remain hermetically sealed and a high vacuum.

What energy can particles be given in accelerators? The largest accelerator possible on our planet would have to be located at the Equator. The intensity of this enormous magnet would be determined by the saturation of steel and would be approximately 20 000 oersteds. In those conditions the maximum energy of accelerated protons would be 10^7 GeV.

Cosmic schemes are characteristic of the space era. One is the 'lunatron'. An accelerator is accommodated in several artificial satellites orbiting the Earth. The focusing magnets, accelerating plates, and injectors would be installed in satellites. With such a system it would be theoretically possible to obtain energies of the order of 10^5 GeV. The 'lunatron's' great advantage would be that it would not be necessary to create a vacuum for the working space as it would already be outside the atmosphere in natural conditions of high vacuum.

G.I. Budker, Member of the USSR Academy of Sciences, suggested an extremely interesting idea, of creating a powerful circular beam of electrons by means of a weak inducing field. To all intents and purposes this beam would be a flexible conductor along which a very high electric current would flow. An electric current always sets up a magnetic field that tends to constrict the cross-section of the conductor (pinch effect). But the smaller the diameter of the conductor, the higher will be the magnetic field creat-

ed on its surface by the same electric current. Budker proposed using a very strong magnetic field as the working field of the accelerator. In a beam of electrons six metres in diameter it would be possible to obtain protons with energies up to 10 GeV.

Physicists set great hopes on superconductivity. The induction saturation of steel (about 20 000 gauss) limits the magnetic field of accelerators; but if it is not used many other problems arise, for example resistance to the magnetic flux increases. In order to maintain the flux at its former level it is necessary greatly to increase the capacity of the supply coil (and in an accelerator with steel this power is enormous). The power supply of the American Bevatron is 100 000 kW, which is equivalent to the amount required by a town with a population of 100 000.

When examining the plan for the Bevatron the Pacific Coast Gas and Electric Co. was particularly concerned whether all the lights in the towns of Berkeley and Oakland would be dimmed when each beam of protons was speeded up in the accelerator.

But the Bevatron is a comparatively small accelerator; it uses steel as well. In accelerators of 300 to 1000 GeV without steel the need for electricity would be much greater and the accelerator itself would be correspondingly more expensive and cumbersome. What is more this colossal amount of energy would be largely spent to no purpose. No energy is required to maintain a magnetic field; a permanent magnet has no source of energy and its magnetic field does not expend energy in attraction. Energy is only needed to create the field: if in an area of space there is now a magnetic field where there was none before a certain amount of energy must have been expended. The rest of the energy goes on heating the coil, which possesses electrical resistance. If it had no resistance the loss would vanish. The amount of energy in accelerators put to good use is therefore in fact insignificant.

It is just that which stimulates attempts to use superconductors as the material for the coils of accelerator magnets. A superconductor has no ohmic resistance, so that consequently there would be no loss of energy. Another positive aspect of using superconducting coils would be the possibility of greatly increasing the magnetic field and thereby reducing the radius of the accelerator; for a field of 100 000 oersteds the radius could be reduced by 80 per cent.

So, one way or another, large accelerators and magnets will be built, for all our atomic projects and our knowledge of elementary particles are based on information obtained from accelerators. New, more powerful ones would seemingly help (a) to explain the innermost secrets of matter and (b) to use the facts obtained for the technology of the future.

Magnetic Traps for Thermonuclear Research

In which we talk about how magnets are helping to tame thermonuclear reactions.

Uranium fission can now be considered well mastered; and the cost of atomic power is now already comparable with the cost of power from thermal power stations. But reserves of radioactive elements capable of being split are not unlimited. The energy obtainable from the uranium and thorium to be found on Earth is about 100 times as much as the energy obtainable from conventional fuels. But there is as much water—the fuel used in the synthesis reaction—as we need. I.E. Tamm, Member of the USSR Academy of Sciences, has written that as much energy can be extracted from the deuterium in one litre of water as from 350 litres of petrol. So the energy of the five oceans is equal to 1750 oceans of petrol. Even with a hundredfold

increase in demand, such a supply of energy should be sufficient to last man for thousands of millions of years.

We must not forget that the waste from conventional atomic power stations is highly radioactive. If, for example, the USA generated all its electricity in atomic power stations, the radioactivity of the wastes would be colossal, equivalent to that caused by exploding 200 000 atomic bombs; and by the year 2000 it would be equal to the radiation from 8 million atomic bombs in a year. That is clearly too great a price to pay for power. In contrast, synthesis reactions, or thermonuclear reactions as they are called, are 'clean' as regards radioactive contamination.

To master controlled thermonuclear reactions, however, is much more complicated than it seemed at first. We must stress the 'controlled' because the hydrogen bomb, in which a thermonuclear synthesis occurs, is an example of an uncontrolled thermonuclear reaction. One of the serious difficulties facing physicists is that the plasma escapes from the 'magnetic bottles' that hold it. What are these 'magnetic bottles'? And why are they needed?

The purpose of a controlled thermonuclear reaction is to give man electric energy, for electric energy has the advantage over other forms of energy that it can be converted more efficiently and easily into other forms of power.

During a controlled thermonuclear reaction it is possible to obtain electricity from the kinetic energy of the hot gasses, from the energy of the light pulses, and from the thermal energy.

A thermonuclear reaction occurs when the nuclei of approaching deuterium or tritium atoms acquire such high energy that they can overcome the electrostatic forces of repulsion and so collide and interact with each other. This happens only when the gas has been heated to a temperature of several million degrees, at which matter takes the form of strongly ionized gas or plasma.

What sort of vessel can withstand such a high temperature? If plasma, heated to millions of degrees, simply touches the walls of the vessel, it will either cool to a temperature such as to make the reaction impossible or vaporize the wall, as the steel tower was vaporized in the thermonuclear explosion at Bikini. No material can withstand such high temperatures and so the question arises: how can we contain the plasma? In the Fifties scientists all over the world devoted much attention to this problem.

The physicists of the Soviet Union, the USA, and Great Britain, which were then the atomic Big Three, though separated from one another by impenetrable barriers of secrecy, began work on it about the same time. When after I.V. Kurchatov's report in 1956 at Harwell on the Soviet programme of thermonuclear research the barriers of secrecy were removed it turned out that they had come to the same conclusion, that the only way to contain plasma without cooling it was to use a magnetic field. Though invisible and intangible, its network of lines of force would hold the plasma away from the walls of the vessel, which would otherwise be reduced to ashes.

The idea of magnetic thermo-insulation of plasma is based on the known property of electrically charged particles moving in a magnetic field to follow a curved trajectory and move in a spiral along the lines of force of the field. In a non-uniform magnetic field this bending of the trajectory throws the particle out at the place where the field is weakest. The problem then was to surround the plasma on all sides with a stronger field. Many laboratories worked on its solution.

When there is ordered movement of some sort in one direction in plasma, it means that the plasma is in effect a flexible column with an electric current, because by definition an electric current is the ordered movement of charged particles.

Every current creates a magnetic field around itself,

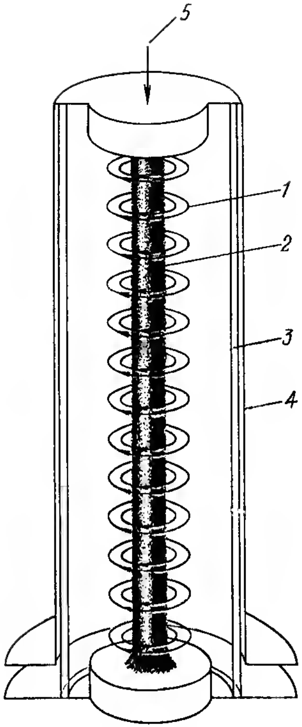

Fig. 28. The pinch effect. A current flowing in plasma sets up a magnetic field around it which constricts the plasma into a thin column in the centre of the vessel. In principle this should make it possible to keep plasma away from the walls of a vessel and so provide magnetic thermo-insulation of the plasma.
1—magnetic lines of force; *2*—constricted plasma column; *3*—insulating wall; *4*—conducting wall; *5*—direction of current.

and lines of force encircle the conductor along which it flows. One of the most important properties of lines of force is that they tend to take the shortest path, so that their pressure and Maxwell tension lead to their striving to constrict the conductor carrying the current. With conventional copper conductors the pressure of the lines of force cannot reduce the diameter of the wire because the crystal lattice of solids is a firm skeleton quite difficult to deform.

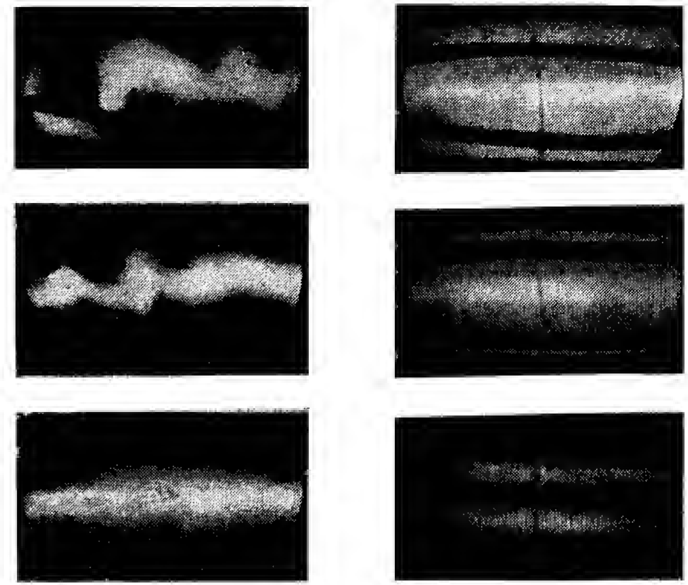

Fig. 29. Pictures of unstable plasma. It is still, unfortunately, not possible to find the shape of magnetic field that will preserve the shape of the plasma for long and prevent it from touching the walls of the vessel.

When current flows along a plasma column the pressure of the lines of force surrounding the column will constrict its cross-section and cause it to move away from the walls of the chamber containing it. This phenomenon, called pinch effect, seemed to answer the problem of magnetic thermo-insulation of plasma (Fig. 28). It seemed it would be worthwhile to 'arrange' the current in the plasma so that it would pull itself away from the walls and constrict it into a fine column or pinch in the centre of the vessel.

But here the property of charged particles (and plasma is a multitude of charged particles—positively charged atoms stripped of their electron shells and electron shells separated from their atoms) to be rejected to the area where the magnetic field is weakest, came into play.

And this ejection of particles (and of plasma as a whole) where there are fewer lines of force, i.e. where they are less densely concentrated, continues to play dirty tricks on physicists. Because of it, the first thermonuclear apparatus based on the 'pinch effect' proved comparatively inefficient, for the slightest imperfection in the plasma column, be it a bend or a local constriction, in the end led to breakdown (Fig. 29).

Let us suppose, for example, that a small bend has formed by chance in the column. In the convex part of the bend the lines of force of the magnetic field will be further apart, and in the concave part denser. The column begins to be pushed out from the region where the lines of force are more densely concentrated to the walls of the chamber. The bend will then increase until the plasma touches the walls of the chamber. It behaves just like a long compressed spring that is unstable under transverse pressure. In exactly the same way a local constriction in the plasma column will increase until the column itself breaks.

A magnetic field helps combat these phenomena. If there are lines of force of a magnetic field from an outside source along the plasma column their pressure should ensure that any curve or constriction forming accidentally will be removed, approximately the same as happens when stretched elastic strips are put inside springs. So, to restore stability more quickly it is necessary to create a very strong longitudinal magnetic field in the plasma.

Another effective way of overcoming bending in the plasma column, especially bends of large radius, is to employ a more or less massive metal casing or vessel to contain the plasma, with a magnetic flux between the casing and

the column, i.e. a magnetic field with conventional lines of force. If the column moves out of position, the magnetic field between the lines of force and the casing becomes distorted and changes shape, the lines of force being compressed in one place and spread out in another. And if we remember that magnetic lines of force are elastic it will be clear that they will strive to return the plasma column to its former position along the axis of the chamber.

The stabilizing of plasma with a longitudinal field is especially effective when the field can be made to exist in the plasma only and not outside it, i.e. when there is no field between the walls of the chamber and the column. This can be done when the plasma column constricted by a strong current carries with it all the lines of force of a longitudinal field set up in the whole volume of the chamber. In pulling away from the walls the column takes with it all the lines of force previously existing in the chamber, creating a magnetic vacuum for the longitudinal field between itself and the walls.

All these ideas began to be tried out in practice during the Fifties. Earlier, it is true, at the end of the war, experiments were being made in the USA on the magnetic containment of plasma. They were directed to military ends and were supervised by Enrico Fermi and Edward Teller, two of the men who built the American atomic bomb.

Intensive work on controlled thermonuclear synthesis began almost simultaneously (as we have said) in the USSR, the USA and Great Britain. The first apparatus was a glass, china or quartz torus-shaped chamber* (later chambers were generally made of thin rustproof, unmagnetized steel) into which were put working chambers, sometimes called liners, with thick copper walls. Around the chamber wound a

* A torus is a ring-shaped solid or doughnut of circular cross-section.—*Tr.*

coil that set up a longitudinal, stabilizing magnetic field of 500 oersteds. The chamber within the torus was filled with gas forming a circular gas coil that acted like the secondary of a transformer. The outer, metal casing of the chamber, attached to a powerful accumulator, served as the primary, though sometimes a conventional copper coil was used. And in order to improve the magnetic connection an iron core was put inside the torus.

One of the first machines called Zeta* consisted of two separate cores with circular inner apertures in which the discharge chamber was located. The cores, which had an inner diameter of 1.5 metres and an outer diameter of three metres, were coiled from transformer steel strip.

When a powerful pulse of current is discharged from the accumulator to the primary of such a transformer, an electric current is also set up in the secondary gas winding, passing along the gas, heating it to a high temperature, and turning it into plasma. And the current itself constricts the plasma column and takes it off the walls.

Other early experimental machines had a similar design. The results of the numerous experiments performed on them, however, made the scientists pessimistic. It became clear that the stabilizing longitudinal field, contrary to the original predictions, could do little to stabilize the plasma column during chance upheavals of any sort. The longitudinal field was too weak in comparison to the plasma's own field. The elastic strings inside the spring proved too weak to protect it from damaging curves.

In order to overcome this difficulty it was necessary greatly to increase the longitudinal field and to weaken the column's own field. The problem was resolved by Tokamak**, in which powerful coils maintaining a pressure of

* The name of the British apparatus at Harwell, an acronym from Zero Energy Thermonuclear Apparatus.

** From the Russian for toroidal chamber with magnetic axial control.

100 atmospheres in the magnetic field were used to create the longitudinal field. These huge solenoids had to be fed from the powerful pulse generators normally used for synchrotrons. Although the magnetic field thus created was pulsed (the pulse lasted approximately one-fifth of a second) it was 100 times greater than the length of the discharge and in relation to it was practically constant.

The longitudinal field of Tokamak was as high as 35 000 to 50 000 oersteds, i.e. 100 times stronger than the field in Zeta.

But how were they to avoid the radius of the column being constricted by pinch effect? As the radius diminishes the column's field grows and the advantages obtained from using a powerful longitudinal field would be wiped out. But if the column's field is weak the column remains too thick and so touches the walls of the chamber and cools. In order to overcome this contradiction the builders of machines like Tokamak decided to put a diaphragm in the toroidal chamber with openings that were small in comparison with the diameter of the chamber. Experiments showed that the cross-section of the column would then not exceed the size of the apertures in the diaphragm. In Tokamak-3, which was built at the Kurchatov Institute of Atomic Energy in 1962, the aperture of the diaphragm had a diameter of 20 centimetres, the liner a cross-section of 40 centimetres, and the external casing a diameter of 50 centimetres. The diameter of the torus was two metres. Eight coils with an outer diameter around one metre set up a longitudinal field of 40 000 oersteds. Each coil consisted of 352 copper turns baked in epoxide resin; and they were fed by an impact generator, i.e. one that worked for only a short period, with a power of 75 000 kilowatts. In 1964 an improved installation Tokamak-5 was commissioned, in which the position of the plasma column in the chamber was automatically adjusted, and later Tokamak-6 (Fig. 30). The tempe-

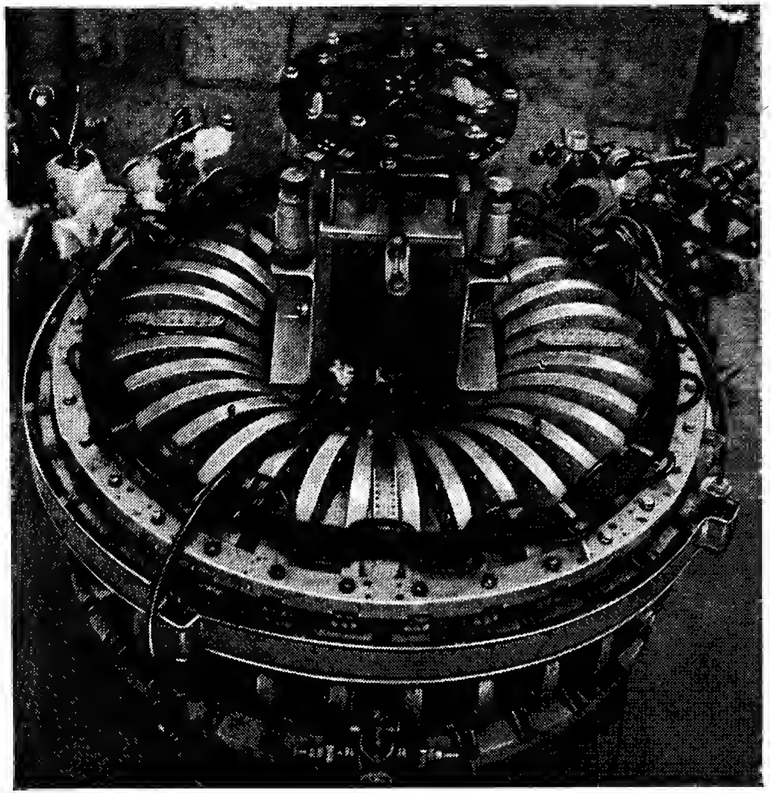

Fig. 30. Tokamak-6, at the Kurchatov Institute of Atomic Energy. Soviet scientists put great hopes in it to help them achieve the physicists' dream of controlled thermonuclear reactions.

rature of the plasma in Tokamak is as high as seven million degrees, which is only one-fifteenth of what is needed. In the much improved Tokamak-10 it is expected to obtain temperatures as high as 30 million degrees.

The results of the experiments on the Tokamak series were very encouraging and it seems likely that similar systems will be used in future research.

Reasonable results were obtained from the Levitron at the Livermore Laboratory. This idea, proposed by A.D. Sakharov early in 1951, was that plasma constricted by its own field would experience supplementary constriction from the magnetic field of a special conductor placed in the centre of the plasma column, but of course isolated from it. In Levitron, the plasma column was ring-shaped and extremely stable. But the need to isolate the circular stabilizing conductor from the plasma, and to fix it in the centre of the chamber, reduced chances of the system finding wide practical application.

An article written in 1950 by Sakharov and Tamm opened up a completely new dimension in the work on the magnetic containment of plasma. They proposed containing it in magnetic traps (or 'magnetic bottles' as they are often called) and relegating the plasma's own magnetic field to a secondary role. The first trap they suggested was a torus-shaped chamber with a longitudinal magnetic field. Any charged particle injected into the chamber would move in such a way that its trajectory 'wound' onto the magnetic lines of force. But they soon found a serious defect in their own system. It turned out that the intensity or induction of the magnetic field (the density of the lines of force) in the torus-shaped chamber, in which the magnetic lines of force were distorted, was higher inside the walls of the tube than outside. The explanation was that the pressure of the lines of force impelled them to take the shortest possible route so that more lines of force accumulated on the inner wall where the path was shorter than on the outside wall.

The non-uniformity of the magnetic field altered the spiral orbit of particles. Near the inner surface where the field was stronger they had to move along a shorter orbit than

near the outer surface. As a result they drifted across the lines of force of the magnetic field with positively charged nuclei moving to the 'top' of the tube and electrons to the 'bottom'.

The drift was bad enough in itself but its side effect was simply catastrophic. When particles separated according to their sign an unforeseen electric field was set up within the chamber, which completely distorted their orbits, throwing them against the walls of the chamber.

How can this non-uniformity of magnetic field be avoided? How can all the paths of the lines of force in the toroidal chamber be equalized?

It could be done if a line of force passing along the inner surface of the chamber could be forced to change places at some point with a line of force passing along the outer surface. Then the lengths of all the lines of force would be identical and all would enjoy the same conditions; each line of force having made a full turn would not return to its former spot but would form something called a magnetic surface. This effect could be obtained by bending the lines of force around the axis of the torus, so that they had approximately the same pattern as the strands in a rope.

In a magnetic field, transformed by twisting, particle drift would be reduced to the minimum. For that the magnetic line of force had to describe a circle in the torus at the same time as it twisted constantly around the chamber axis. This would be possible by using a winding with a large pitch, as shown in Fig. 31. Similar windings were used in the Model C Stellarator built some years ago in the USA. In plan the chamber looks rather like the cinder track in a stadium. Its inner radius is 20 centimetres, the length of the axis is 12 metres, and the intensity of the magnetic field is of the order of 50 000 oersteds. The power consumption is 15 000 kilowatts.

The American physicist L. Spitzer and L.A. Artsimovich, Member of the USSR Academy of Sciences, suggested ano-

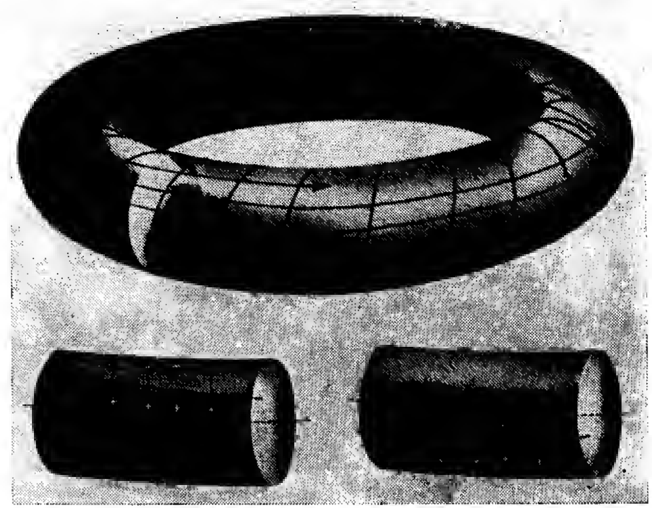

Fig. 31. Physicists have great hopes of the Stellarator, a system in which the magnetic lines of force describe a special surface known as the magnetic surface.

ther method of 'rotational transformation' or 'twisting' of the lines of magnetic force.

We have already spoken of how an ordinary untwisted longitudinal magnetic field has ununiformities which leads to negative particles sinking to the 'floor' and positive particles rising to the 'ceiling' of the chamber. But what would happen if half of the torus remained unaltered and in the other half the 'ceiling' and 'floor' were reversed? That is to say imagine the torus as a doughnut twisted into a figure of eight. Having begun to fall in the first half of the figure of eight a particle would then begin to 'fall upward' in the second half and so remain in the centre at the same distance from the chamber's axis.

Toroidal chambers of the stellarator type that have a spiral winding and have been twisted into figures of eight seem to be the best magnetic systems for containing plasma at the present time. Their drawback is that they are difficult and expensive to make.

A simpler system, for example, is the trap with magnetic mirrors or corks (which Russian physicists jokingly call a 'probkotron' from the Russian word *probka*, cork). It was proposed by Budker and consists of a long tube in which a longitudinal magnetic field is set up. The coils wound round the ends of the tube are more massive than those in the centre so that the lines of force at the ends are denser and the magnetic field stronger. A particle injected into this kind of magnetic bottle therefore cannot escape through the ends of the tube. In 1958 I.N. Golovin built a huge magnetic trap at the Institute of Atomic Energy for Ogra-I on this principle. The vacuum chamber was 19 metres long and had an internal diameter of 1.4 metres. The average diameter of the winding creating the magnetic field was 1.8 metres and the intensity of the field was 5000 oersteds at the centre of the chamber and 8000 oersteds in the mirrors.

But, as it turned out, the 'probkotron' in its 'pure' form also had serious drawbacks. In this system the magnetic field is weakest at the walls in the middle of the channel. The plasma tends to this spot during a discharge and in less than 0.001 second is already on the walls.

A new step toward perfecting the 'probkotron' was made at the Institute in 1963 when the PR-5 was built (Fig. 32). The idea was suggested by B. B. Kadomtsev, who had been trying to discover why the original 'probkotron' had failed, and who had discovered that it was necessary to have a magnetic field with a more complex configuration in order to contain the plasma more successfully. He suggested supplementing the system of magnetic mirrors by another winding along the active cylinder in such a way that the current in neighbouring conductors would flow in opposite

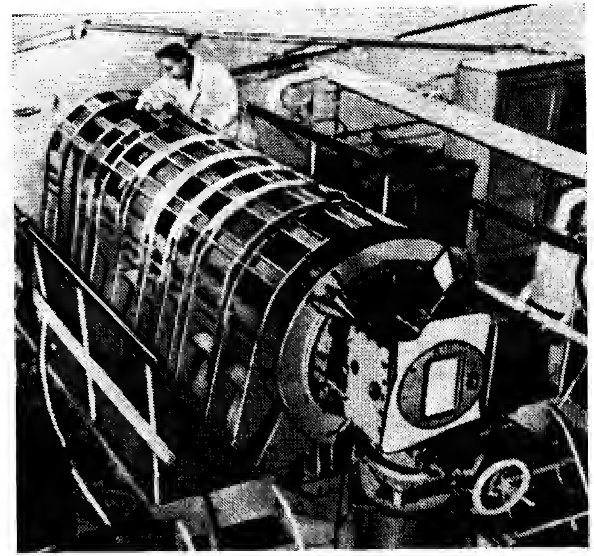

Fig. 32. The PR-5 (Probkotron) magnetic trap.

directions. That should set up a supplementary magnetic field near the walls of the cylinder, and keep the plasma away from them.

By applying a field from rectilinear conductors to the field-tube a magnetic field with a very complex picture was obtained. If, for example, the tube formed by the lines of force in the centre of the chamber has a circular cross-section, at the boundaries of the chamber it will have the shape of a curvilinear triangle.

The apparatus was built by a team of physicists headed by M.S. Joffe. Rectilinear conductors were placed under the coils creating the magnetic field of mirrors. The longitudinal magnetic field was 8000 oersteds in the centre of

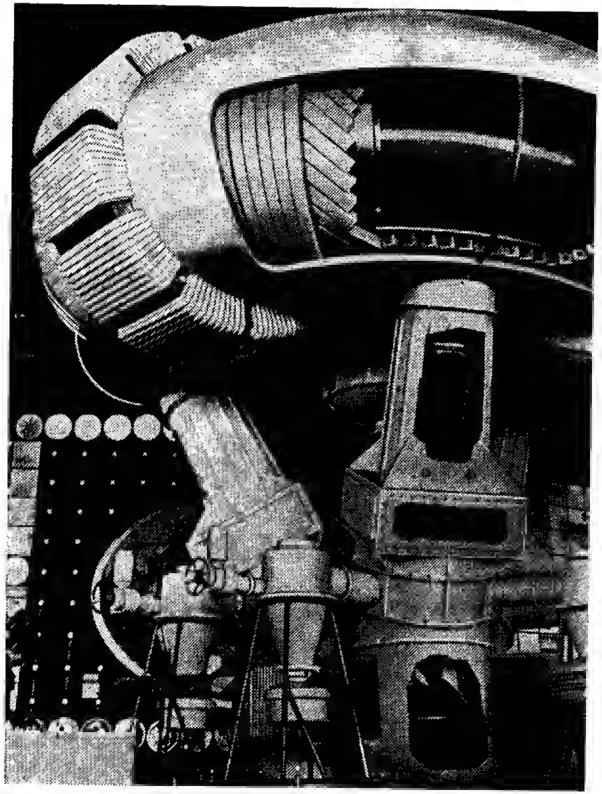

Fig. 33. A thermonuclear reactor of the future. A mock-up in the Soviet Pavilion at EXPO-67 in Montreal.

the chamber and 12 000 oersteds at the mirrors. The magnetic field of the rectilinear conductors was 8000 oersteds near the walls. The working volume was 1.5 metres long and 40 centimetres in diameter. Soviet physicists were greatly encouraged by the results of their first experiments. The

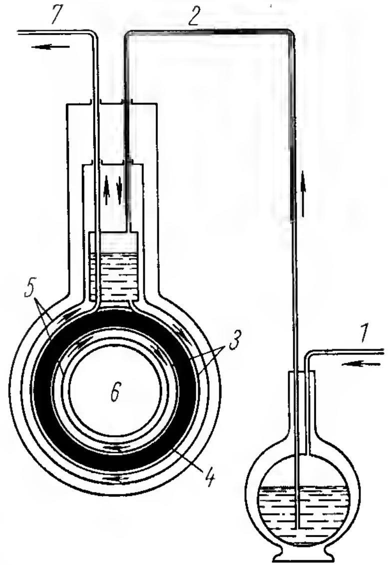

Fig. 34. Schematic diagram of a superconducting plasma trap: *1*—input of gaseous helium under pressure; *2*—input of liquid helium; *3*—spiral heat exchanger; *4*—superconductive coil; *5*—nitrogen screens; *6*—working zone; *7*—exit for gaseous helium.

plasma was 35 times more stable than in the original 'probkotrons' and lasted for several hundredths of a second. In 1964 Ogra-II was built, also on the principle of combined magnetic fields.

It is now accepted in all countries that a complex configuration of the magnetic field is the key to long-lived plasma. Magnetic systems with opposing fields, as in Orekh (the Nut) in which the direction of the current from one of the mirror coils is 'confused', installations with high-frequency mirrors, 'antiprobkotrons', and still more sophisticated machines have already been built, and scientists in the Soviet Union and other countries are working intensively on making other magnetic traps (Fig. 33).

What will a thermonuclear generator be like? The magnetic trap is likely to be very large, for only then will

the power it consumes be small compared with the generator's power. This is the case because the power of the generator is proportional to the cube of the linear dimensions of the system while the power required by the coils is directly proportional to them. Therefore knowing the power required by the magnetic trap we can be sure that a thermonuclear generator will have to be several metres in diameter and several dozen metres long. Only then will its useful power be greater than the energy required by the magnetic system.

'There is little doubt,' L.A. Artsimovich wrote, 'that the problem of controlled nuclear synthesis will be solved in the end.'

It is not excluded, however, that we may well be able to build huge superconducting coils in the future, which would greatly increase the efficiency of generators (Fig. 34).

The cost of electric energy from thermonuclear power stations will be very low because of the cheapness of the initial raw material (water). The time will come when power stations will generate literally oceans of electric energy. And with this power it may become possible not only to alter the nature of life on the Earth radically (to reverse the flow of rivers, drain marshes, and irrigate deserts), but also to change the appearance of near-by outer space—to inhabit the Moon and to give Mars an atmosphere.

One of the basic difficulties is clearly that of creating a magnetic field of set shape and strength. The strength of the field in contemporary thermonuclear traps is relatively small considering the huge volume of the chambers, the absence of a ferromagnetic core, and the special shape of the field required, which all make the building of such systems much more difficult but it must be admitted that the traps we already have are a great technological achievement. The traps that will replace them will be the pride of a new branch of physics—the physics of high and superhigh magnetic fields.

THE KEY TO THE MAGNET

Giants Should Become Extinct

In which our basic aim is to show that the electric razor is not the only device that uses electromagnets and that today's gigantic magnets are already giving engineers a slight feeling of irritation, and sometimes not so slight a concern.

At the end of 1962 the American International satellite suddenly stopped giving the signals that witnessed that it was functioning properly. A little later Transit, which crossed exactly the same region, broke off its broadcast in mid-sentence. Attempts to restore communications failed.

Investigations gave the following explanation for all these mysterious space accidents. In July 1962 American atomic scientists exploded Starfish, a one-and-a-half megaton nuclear device, 400 kilometres above Johnston Island. The explosion caused indignation throughout the world, and created an artificial radioactive belt at the centre of which the hourly dose of radiation was 500 times the lethal dose for humans. The powerful currents of electrons given off by this nuclear explosion damaged the radio apparatus of the artificial satellites.

The same effect, only on much bigger scale, should be met in the natural radiation belts of the Earth. The danger that these radiation belts present has attracted special attention since man first went into space.

At first glance the problem of protection against radiation might not seem so complicated, particularly since

Nature offers us a marvellous example of how she has solved it. For that matter, if there is so much dangerous radiation in the space around the Sun, how is it that the human race has survived? Why has the Earth not been turned into a desert, a lifeless plain?

As we said earlier, the Earth is protected against radiation by its own magnetic field. As soon as a charged particle enters this field its path is deflected and it begins to orbit the Earth, revolving along the lines of force of the magnetic field.

Therefore a magnet can be used to protect a spaceship against radiation. It would have to be approximately equal to the diameter of the ship, of course, and the field strong enough to repel dangerous particles.

This problem did not seem to be too complicated. After all, in the 150 years since Sturgeon made the first electromagnet engineers have learnt how to make electromagnets of appropriate dimensions and with quite strong fields. And since Arago and Ampère demonstrated that a spiral carrying direct current behaves in exactly the same way as a natural permanent magnet, attracting small bits of iron, all modern electromagnets have worked on that principle; each always has a spiral (usually copper or aluminium) that carries a current.

Theoretically there is no limit to the intensity and induction of a magnetic field of an electromagnet. The power lost in the electrical resistance of the coil is the sole obstacle to obtaining super-high magnetic fields; and it increases with the square of the intensity of the required magnetic field. The record permanent electromagnet, built in the USA with a water-cooled copper spiral, creates a magnetic field with an induction of 250 000 gauss and consumes 60 megawatts. One scheme for an electromagnet with a field of one million gauss envisages supplying it from generators with a total power of 1000 megawatts.

In order to reduce the power required by an electromagnet a steel core is put inside the spiral. The power can be substantially reduced this way but the weight of the magnet is increased 100 fold by the steel armour around the inside and the outside of the spiral. Such magnets are used for small fields of set uniformity (up to 20 000 gauss) as in the magnetic systems of charged particles accelerators.

But quite obviously heavy magnets cannot be used on spacecraft. So if magnetism is to be used as protection from radiation it can only be done with relatively light systems without steel cores. It seemed as if the solution lay along these lines. But the calculations did not support the idea. An electromagnet in the form of a water-cooled copper coil would have to weigh twenty or thirty tons, or more, in order to meet the demands put on it and would need a power station and a pumping station installed on the spacecraft to serve it.

A new type of magnet was clearly needed that would be light, compact, and highly economic, quite unlike the multi-ton copper and steel monsters that have occupied huge physics laboratories and the underground lairs of gigantic synchrophasotrons.

It is difficult to imagine how complicated it was to create new magnets. We can now say 'was' because thousands of such devices have already been tested in the laboratory. They are not only intended for outer space, after all many terrestrial branches of science and technology are connected in some way or another with the application of magnetic fields.

This is probably the best place to explain what magnets we shall now be concerned with. We use magnets very often in our daily life—every time we switch on an electric razor, a tape recorder, a vacuum cleaner, a radio set, an electric floor polisher, or a television set. But these magnets are relatively weak; their fields are nowhere near 10 000 gauss (ten kilogauss) and the volume in which they operate is measured in cubic millimetres.

But that is not the type of magnet we are concerned with. Twentieth-century physics and technology use magnets hundreds of times larger in physical size and in strength than these little devices.

Modern generators producing oceans of electricity have 10 to 15-metre rotors revolving at high speeds. Those are magnets.

In magnetic fields half a million times stronger than the Earth's, scientists are researching into the properties of matter. In these fields a force greater than two tons per square centimetre of the coil's surface is exerted. The apparatus to produce them occupies a whole laboratory block. It is also a magnet.

One can name hundreds, even thousands of the most varied physical, technical, and purely practical engineering jobs that have one thing in common, that they all require light, powerful, economic magnets. It is a matter of building new generators, of diving work to raise sunken ships, of atomic factories, and of effecting controlled thermonuclear reactions.

A powerful magnet is the key to all these and to many other problems. But the key to it has eluded scientists for a long time.

Why do available magnets not suit engineers and scientists? To begin with because, as we have said, they are too voracious.

Whereas laboratory electromagnets of 20 000 gauss need power measured in hundreds of kilowatts, magnets dozens of times that strength would need a power source hundreds of times stronger, of the order of tens of thousands of kilowatts (or tens of megawatts).

Things are no better as regards size. Since it is difficult to obtain a field higher than 20 kilogauss with steel magnets designers have frequently had to increase the size of the magnets in order to achieve the desired effect. And so the magnets of accelerators are hundreds of metres in diameter

and the more powerful pieces of nuclear artillery, being planned or built, have magnets with diameters measured in kilometres.

And that does not exhaust the deficiencies of 'traditional' magnets. They are naturally very heavy (basically because of the steel armour of the core which is used, not very successfully, to lower power requirements). The giant magnet in the Dubna synchrophasotron, for example, weighs 36 000 tons, the weight of several long, fully loaded railway trains.

And in the future? How big and heavy and voracious will powerful magnets be? For it is clear, that with the increasing sophistication of scientific and engineering problems and the growth of industry, these already huge figures, which are evidence of the serious drawbacks of the magnets, will go on becoming larger and larger.

But that will not happen. And here is why.

Mistake or Discovery?

In which an eminent Dutch scientist, after long doubts, communicates a new discovery to the world.

An eminent physicist once said that the modern scientists involved with superconducting magnets 'have stolen the pie from Onnes and are gobbling it up'. But actually there is as big a difference between modern superconducting magnets and Kamerlingh Onnes's ideas as there is between a pie and its recipe. Back in 1911 the Dutch physicist Kamerlingh Onnes while working in his Leyden laboratory accidently stumbled upon the phenomenon of superconductivity and at first took it for an error in his experiments.

And it was a very long time before he realized that superconductivity was not an experimental error or proof of his incorrect theory of electrical resistance but a totally

unknown, unexplained phenomenon heralding a new era in electrical engineering.

Here are the stages that led up to the obtaining of super-low temperature and to the discovery of superconductivity:

1877—the Frenchman Louis Cailletet obtains liquid oxygen in the form of drops of mist (90.2°K).*

1883—the Poles Z. Wroblewski and K. Olszewski produce liquid nitrogen (77.4°K).

1898—the Scotsman James Dewar produces liquid hydrogen (20.4°K).

1908—the Dutchman Kamerlingh Onnes first obtains liquid helium as a small cloud of mist (4.2°K).

1911—Kamerlingh Onnes discovers superconductivity in mercury.

Before 1911 it had not been clear how the electrical resistance of metals would change as their temperature was lowered. There were then three schools of thought.

1. It was known from the classical theory of electromagnetism that the resistance of a conductor diminished as its temperature fell and it was fairly simple to explain the phenomenon. An electric current is a flux of free electrons passing through the crystal lattice of a metal. The probability of electrons colliding with the lattice at hight temperatures is great because of the thermal oscillation of the atoms in it, an oscillation that hampers the movement of the electrons and sets up a resistance to the current. At low temperatures, when the amplitude of oscillations of the atoms in the lattice decreases, the probability of electrons colliding with the lattice diminishes and so the current encounters less resistance. At absolute zero the lattice would be still and the resistance of the conductor zero.

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* The Kelvin scale is used here. Temperature is read from absolute zero (0 °K= —273.16 °C).

2. Even at absolute zero there would be resistance to current because some electrons would collide with the crystal lattice, especially as the lattice is not, as a rule, perfect, but always contains defects and includes impurities.

3. The resistance of metals should increase as one nears absolute zero because, as the electrons condense on the lattice (a crude analogy would be the formation of drops of water on a cold spoon when it is held above a cup of hot tea), they will continuously grow fewer in number as the metal cools; consequently the electrical conductivity (which is the opposite of resistance and is determined by the number of free electrons) will decrease.

In the spring of 1911 Kamerlingh Onnes froze some mercury in a Dewar flask containing liquid helium. Then he passed a current through the mercury and observed on his meters how, as he expected, resistance fell with temperature. The correlation between resistance and temperature was maintained until the temperature fell to 4.12°K. Then electrical resistance suddenly disappeared; there was not even any resistance in the mercury due to defects and impurities in the lattice.

He repeated the experiment. He took some very impure mercury so that the residual resistance caused by the impurities should be clearly noticeable. But close to the same temperature, 4.12°K, resistance almost as suddenly vanished. How could the resistance of the column of mercury be increased so that it could be measured on the meters? It was apparently necessary to increase the length of the column and reduce its cross-section. He prepared a column of mercury finer than a human hair and 20 centimetres long. He measured the resistance again and was astounded to see that the meters did not move.

He made a ring of mercury and hung it on a fine thread. If a current were induced in the ring (for example by switching off an electromagnet) the thread would revolve through

a certain angle, which could be measured with great accuracy by fixing a small mirror on the thread and following the reflection. If there were any resistance in the ring the current would be gradually extinguished. The twist of the thread would weaken and the reflection would move. He carried out the experiment. The reflection did not move.

It could only mean that there was no electrical resistance in the ring, i.e. that the mercury was superconductive at temperatures near absolute zero. But it was more than half a century before superconductivity ceased to be a laboratory curiosity and became sure ground for physicists and engineers.

Some Properties of Superconductors

In which we largely stick to our title but also range over the Universe, 'Mahomet's Grave' and the mysterious theories known as BCS and GLAG.

The best known and, apparently, valuable property of superconductors is their zero electrical resistance to direct current.

It is impossible to prove the fact of zero resistance experimentally; all one can say is that the resistance of a superconductor is not greater than the smallest unit measurable on the instruments. The upper limit of specific electrical resistance in a superconductor is considered to be 3×10^{-23} ohm-centimetre*. From that it is possible to calculate that the current in a superconducting circuit is reduced by an amount that can only be observed experimentally over a period of not less than 100 000 years. It is now understandable why, in one of the experiments carried out from March 1954 to September 1956, the researchers failed to notice the slightest fall in the current in a lead circuit. An experiment that took ten years yielded the same result.

But during research into the fading of magnetic flux inside a niobium-zirconium tube (25 per cent zirconium) it was found that the flux did die away in logarithmic progression; in the first second it fell by 1.0 per cent, in the next ten seconds by 1.0 per cent, and so on. To fade away completely, or rather to the point where nothing is measurable by means of modern instruments, would take 10^{92} years. It follows, of course, that one has to approach the results of such experiments warily. Any ring creating a magnetic field is known to experience forces tending to increase its size or simply to disrupt it. An increase in the diameter of the ring, if only by one millionth, would immediately be reflected by a fall in the field, which might be ascribed to the presence of electrical resistance in the superconductor.

It was 22 years after the first, main property of superconductors—the absence of resistance—was (in 1911) discovered that their second major property became known. In 1933 the German physicists Meissner and Ochsenfeld discovered that superconductors were ideal diamagnets. What did that mean?

We, for example, are always in the Earth's magnetic field. Its lines of force penetrate everything around us. When anything ferromagnetic, like a piece of iron, comes into their path they become denser. But when they meet a dimagnet they spread apart and form a vacuum of lines of force. Magnetic lines of force do not generally penetrate a superconductor. In other words a superconductor is a perfect diamagnet; its interior is ideally screened from

* At 4.2 °K copper has a resistivity of 1.0×10^{-9} ohm-centimetre, which is at least 33×10^{12} greater than that of a superconductor. So copper is often used as an electrical insulator for superconducting wire.

external magnetic fields (the Meissner effect) by currents flowing in a thin layer at its surface. A magnetic field penetrates this layer (to a distance known as the penetration depth and signified by λ). The diamagnetism of superconductors can be used to give the lines of force of a magnetic field a certain configuration, for example, the field passing around the superconductor and the lines of force adopting its contours.

A superconductor differs essentially from an ideal conductor with a resistivity $\rho=0$. A magnetic field can penetrate an ideal conductor but there is no way to force one to penetrate a superconductor.

Or rather there is one way: when the intensity of a magnetic field rises above a certain critical value at one point of the superconductor the latter is no longer at that point in a superconducting state. This critical field is low for pure metals and does not exceed hundreds of oersteds, as can be seen from Table 2.

A current flowing through a superconductor can also cause it to lose superconductivity. In pure superconductors its strength is linked with the critical magnetic field by Silsbee's rule, i.e. that superconductivity is quenched by a current in the conductor strong enough to create a field on its surface equal to the critical magnetic field. The strength of the field on the surface of the conductor can be established from the Ampère Law.

Every superconductor also has a critical temperature, the transition temperature (T_c) above which it suddenly loses its superconducting properties. These temperatures vary widely (see Table 2).

The mechanical stresses in a specimen affect the critical temperature, but only weakly. As a rule, but not invariably, an increase in mechanical stress causes a rise in the critical temperature. It is only possible to ascertain this by highly sensitive methods.

Table 2

Transition Temperatures and Critical Magnetic Fields of Selected Metals

Element	Transition (or critical) temperature T_c, °K	Critical magnetic field H_c, oersteds
Titanium	0.4	100
Ruthenium	0.49	66
Zirconium	0.55	47
Cadmium	0.56	30
Uranium	0.6	~2000
Osmium	0.71	65
Zinc	0.82	52
Gallium	1.1	51
Aluminium	1.2	99
Thorium	1.37	162
Rhenium	1.7	201
Thallium	2.39	171
Indium	3.4	278
Tin	3.72	309
Mercury	4.15	411
Tantalum	4.4	780
Vanadium	5.30	1310
Lanthanum	5.95	1600
Lead	7.17	803
Niobium	9.22	1944

An analogous dependence exists between mechanical stress and the critical magnetic field. It has been shown, in particular, that the critical field of a specimen of tin, which is 210 oersteds at 2°K, is raised to 15 000 oersteds after strong mechanical stresses had artificially been set up in the tin.

Diminishing the size of a specimen to approximately one micron causes an essential change in the properties

of a superconductor; it is no longer diamagnetic and its critical field and current increase abruptly.

By reducing the thickness of a specimen its critical field can be increased one hundred fold. A superconducting lead strip 20 angstroms thick has a critical field of 400 000 oersteds.

The density of the critical current in thin superconducting strips also rises quickly. In layers around 100 angstroms thick it reaches 10^7 to 10^8 amperes per square centimetre.

When the frequency of the magnetic field or the current is increased a superconductor gradually begins to acquire resistance, but at frequencies under 10^7 hertz it is still practically zero.

In 1950 the American physicist A.B. Pippard established that the range of critical frequencies for tin was between 1.2 and 9.4 gigahertz (1.2-9.4 GHz).

As L.N. Cooper, a young American scientist, showed in 1956, electrons form pairs in the superconducting state, the formation of these pairs becoming possible when the interaction of the conduction electrons with antiparallel spins (roughly speaking, turning in opposite directions) and the lattice* gives rise to forces of attraction between them that overcome the forces of electrical repulsion.

The dimension of the Cooper pairs is quite large, greater than the penetration depth in pure conductors and rather less in alloys.

On the basis of Cooper's postulate a theory of superconductivity, known as the BCS theory after the names of its authors—J. Bardeen, L.N. Cooper, and J.R. Schrieffer*—was developed, and also N.N. Bogolyubov's theory.

Energy must be expended to disrupt the Cooper pair. Therefore the energy of the superconducting electrons is smaller than the energy of normal electrons by a definite amount, the difference being known as the energy gap.

Pure superconductors (with the exception of niobium) are of the first kind, but most (and around 1000 have already been discovered) belong to the second kind, a term introduced in 1952 by the Soviet scientist A.A. Abrikosov in further developing the GL (Ginsburg-Landau) theory. The term is essential for distinguishing superconductors with a negative surface energy from those with a positive surface energy (first kind) at the transition from the superconducting phase to the normal one. Negative surface energy occurs when the Ginsburg-Landau parameter k is greater than $1/\sqrt{2}$.

Superconductors in which k is greater than $1/\sqrt{2}$ are mainly the various superconducting alloys. From the GLAG theory (from the names of V.L. Ginsburg, L. D. Landau, A.A. Abrikosov, and L.P. Gorkov**) it follows that the critical fields and transition temperatures of superconductors of the second kind should be very high. J.E. Kunzler's discovery in 1961 of the superconductivity of Nb_3Sn in a field of 88 000 oersteds verified this theory. It later became clear that the critical fields of many alloys (like Nb_3Sn and V_3Ga) exceed 200 000 to 250 000 oersteds and that these alloys have higher critical fields and transition temperatures than superconductors of the first kind. It is possible that superconductors with even better superconducting properties will be discovered in the near future.

* The role of the lattice in the development of the superconducting properties was demonstrated in 1950 by E. Maxwell, who discovered the isotopic effect, i.e. the dependence of the critical temperature on the frequency of oscillation of the lattice (the mass of the atom).

* Bardeen, Cooper and Schrieffer received the Nobel Prize in 1972 for this work.

** Gorkov substantiated the equations of the Ginsburg-Landau theory.

But theoretical physicists do think that there is a limit to the properties of superconductors and take the limit of critical temperature to be 40°K, which applies to the type of superconductivity now known, in which an electron pair capable of moving through the lattice without friction is formed by the field of lattice vibrations. In this field one electron emits a vibration quantum and another absorbs it; consequently there is no loss of energy or any electrical resistance.

If the mechanism of superconductivity worked some other way it would be possible to achieve even higher critical temperatures. In the American press there has been a discussion of the possibility of superconductivity in linear polymers at critical temperatures up to 1000°K.

The properties of superconductors of the first and second kinds are strikingly different; in those of the second kind, for example, the transition to the superconducting state proceeds very smoothly with a broad range in the intensity of the magnetic field. A superconductor of the first kind can readily be converted into a one of the second kind by introducing atoms from outside (a few per cent are sufficient) or by deforming its crystal lattice by some means like mechanical coercion. The outcome is paradoxical, the worse the lattice the greater is the critical current in the superconductor.

According to the GLAG theory, alloys should have two, and not one, critical fields. The intensity of the magnetic field below which a superconductor remains absolutely diamagnetic is represented by H_{c1}. At higher intensities the field begins to penetrate the superconductor in the form of fine filaments parallel to the external field and containing quanta of magnetic flux.

In a field H_{c2} a superconductor no longer obstructs the lines of force. So the field can be expanded by increasing the concentration of defects in the superconductor. In very uniform superconductors of the second kind, the theory

predicts, there will be no hysteresis (the loop in the magnetization curve).

Nevertheless, for alloys consisting of large sectors with differing concentrations of defects (or a different composition) the correlations of the GLAG theory are not observed, and they possess very pronounced hysteresis. Such superconducting alloys are sometimes called superconductors of the third kind.

The non-homogeneity of alloys to a significant extent determines their critical current, but has no effect whatsoever on the size of H_{c2}.

Since superconductors of the second kind are permeable to magnetic fields and, having a non-homogeneous composition, are subject to hysteresis, supplying them with alternating current or placing them in a fluctuating magnetic field causes losses. The magnitude of these losses, for a niobum+zirconium alloy (25 per cent zirconium) at 50 hertz, it has been shown, is 300 watts when a current of ten kiloamperes is passed through a superconductor one metre long. The losses can be significantly lowered by reducing the dimensions of the superconductor—by drawing it into fine threads, for example, or pressing it into a porous material.

Such 'synthetic' superconductors have two advantages at least: first, their superconducting properties are improved when their dimensions are reduced; second, losses to eddy currents in the non-superconducting parts are reduced.

The Josephson Effect

In which we tell briefly about a discovery made, surprisingly enough, with a fountain pen, that may possibly become one of the technological sensations of the age, but may equally remain simply an intriguing curiosity of theoretical physics.

Was it foresight? Or the result of many years' hard work? Or a series of happy coincidences? Apparently it was a combination of all three. Some years ago Brian D. Josephson, a research student at Cambridge University, published a short paper in *Physics Letters* that aroused unusual interest among physicists.

Josephson was apparently in a hurry. *Physics Letters* publishes new research that people want to make quickly known, and its publication time had been reduced to six weeks or two months! And it really was necessary to hurry, because a matter of weeks might decide whose name would be given to the new effect.

What was it in Josephson's article that aroused such great interest? Has the Josephson effect any practical application? Or is it just a curiosity?

The Josephson effect is a tunnel effect in superconductors, a mysterious flowing of superconducting, i.e. non-fading, current through a non-superconducting layer dividing two superconductors.

Let us begin with a tunnel effect. What is it? To explain let us make a small experiment.

As you undoubtedly know, a vacuum is an ideal insulator. However thin the vacuum layer is, it reliably insulates electrically charged particles from each other. Now let us take a condenser or capacitor with two plates, to which a constant potential difference is applied. How will the current alter in the circuit if the plates are moved nearer to each other? The answer seems obvious. While the plates are separated, if only by a single angstrom, no current should flow in the circuit. But experiment proved the opposite. At a distance of approximately 100 angstroms (for our purpose it is unimportant how it is done), an electric current begins to flow through the plates. How is that? It is against all the rules. But yes, as the plates come closer together we move out of our classical macroworld into a world where quite different laws operate,

namely the laws of quantum mechanics by which the carriers of electricity, electrons, have exactly the same characteristics as visible light. We now have to judge the behaviour of an electron by the laws that govern light.

We all know what total internal reflection is. When the angle at which light strikes the interface of boundary between two surfaces, e.g. glass and air, is less than a certain, critical, angle the wave coming from within the glass to its surface will not pass out into the surrounding space but will be reflected back into the glass from the interface. So it will not enter the space around the glass; in other words no light will pass out into the air. And in fact we see no signs of it at first. But what is this?

As we bring a second glass plate closer and closer to the interface, we begin to notice a faint luminescence in it. Where does the luminescence come from? For the wave was reflected back from the edge and did not come out into the surrounding atmosphere. It appears that, as we bring the second glass plate closer to the first, an undamped wave is formed in it like that in the first plate and in this case the solution of Maxwell's equation is also unexpected. Outside the glass, it seems, there is an electromagnetic field that quickly fades with distance. If we investigate the reason for the luminescence in the second glass we can say that the light wave has crossed from the one piece of glass to the other through a 'tunnelling' effect.

Approximately the same thing happens whan the plates of a condenser are brought close together. Despite the apparent total reflection of the electron waves from the interface of the metal condenser and the vacuum, there is an electric field in the vacuum that fades with distance from the plates. By bringing the plates close together we obtain what is called tunnel effect.

Tunnel effect is no novelty in physics. It has been thoroughly studied in semiconductors, and intensively in-

vestigated between metals. It is also known between superconductors.

What remained for Josephson?

Superconductors! He had theoretically discovered the tunnel effect between superconductors. But come! It was known! No, it wasn't. All tunnel effects previously discovered had assumed the presence of electrical resistance between the plates; Josephson's barrier itself was superconducting.

Like Leverrier, Josephson had made his discovery with 'the tip of a pen'. To understand his reasoning we must recall a few factors bearing on the theory of superconductivity. The first, perhaps, is the famous superconducting ring, i.e. a ring made from a superconductor, in which a current does not fade.

It has been verified experimentally that the current 'frozen' in the superconducting ring can only be reduced in steps, which corresponds to Bohr's postulate that an electron impulse can only accept strictly defined, discrete values. It has been calculated for single electrons moving along a crystal lattice that the step must equal 4.14×10^{-7} maxwell. B.S. Deaver, Jr. and W.M. Fairbank, trying experimentally to determine the height of the step, came to the unexpected conclusion that the quantum of current obtained was 2.07×10^{-7} maxwell, i.e. half the predicted amount. The divergence could only be explained if we assumed that the carrier of the superconducting current had a double charge, i.e. was a pair of electrons.

A pair of electrons! How could that be? For electrons are negatively charged particles and consequently surely repel each other! What can hold them together? What would unite them?

The first to solve that problem was the American physicist Fritz London. He introduced a totally new idea into the theory of superconductivity that in the end led Josephson to his discovery.

London said that a current is set up in a metal because electrons move by preference through a metal lattice made up, roughly speaking, of positive ions. An electron moving near such an ion attracts the latter to itself so that the whole lattice is distorted; in one region it has more positively charged ions than before, and in another fewer. The region with a surplus is able to attract another electron. In the end, because of the mediation of the lattice, two electrons are attracted, if not to each other, then to the same place, and form a pair. Whether they are strongly or weakly linked depends on the strength of their interaction with the lattice. In metals like copper and silver, which are considered the best conductors of electricity, the link is unstable so that no pairs are formed. By the same token they are not superconductors, for superconductivity arises as the result of the formation of pairs. Nor is that all. If the pairs were to move by themselves in an uncoordinated fashion, they would still be dispersed in the crystal lattice. It is a peculiarity of a superconducting current that all the pairs are closely linked to one another and move in a single system, in a single rhythm, closely intertwined with each other. It is impossible to stop any one pair; its extensive links would result in complete stoppage of all the electrons throughout the volume of the metal. In that sense a superconductor is analogous to a single, gigantic molecule. Therefore only two states are possible for it; either no current flows or it flows without let. In principle a superconductor cannot have electrical resistance.

So a superconductor is a single gigantic molecule, a single organism with a single rhythm, to which all the electron pairs are subordinated. From quantum mechanics we know that any particle possesses wave properties. In that sense a superconductor is a single ocean of waves and the waves are of equal length and, moreover, are all in phase, i.e. coincide with each other, a fact that is especially important for explaining the Josephson effect.

Josephson's contribution was that he wanted to study the concept of phase in superconductors in greater depth. We have already seen how all electron waves in superconductors have the same phase. But what phase? Unfortunately, physicists cannot say exactly. All waves in one part of a superconductor are in phase, and all the waves in another part are also in phase. That is not disputed. The question is whether or not they are in the same phase.

Josephson was unable to demonstrate that they should be the same. Perhaps they were, perhaps they were not. So we get the following picture. One phase is set up in a large section of a superconductor through the powerful mutual influence of pairs. If the superconductor is then cut in two and the pieces separated by a significant distance (say a centimetre, which in atomic terms is an enormous distance), there may now be different phases in them since the mutual influence of pairs is now completely absent. Might there not also be an intermediate state in which different phases and the mutual influence of electron pairs would be preserved? Josephson decided that this could quite possibly happen. If the two pieces of the superconductor were now moved to within an infinitesimal distance of each other, smaller than the dimensions of the electron pairs (ten to twenty angstroms, say), then, as a result of the normal wave properties of electrons, i.e. of normal tunnel effect, the two superconductors with their different phases should exchange electron pairs. And once such an exchange had taken place the barrier between the two superconductors (in its simplest form a vacuum) should be unable to offer any electrical resistance to the movement of pairs, i.e. the barrier would be superconducting. This was the new thing that Josephson had noticed. In addition, he surmised that if different phases were somehow set up in two superconductors, the exchange of electron pairs that would occur when they were sufficiently close together would be more intense in one direction than in

the other. In other words, an unfading electric current should flow across his barrier.

Josephson apparently thought it unlikely that it would be possible to check his theoretical discovery in the near future. For it was easy to say 'move the two bits of the superconductor to within 10 angstroms of each other', but it was quite something else to do.

But within a year of Josephson's communication a paper appeared in *Physics Review Letters* from P.W. Anderson and J.M. Rowell, that opened with the following words: 'We have observed an anomalous dc tunneling current at or near zero voltage (sic! superconducting!—*V.K.*) in very thin tin oxide barriers between superconducting Sn and Pb, which we cannot ascribe to superconducting leakage paths across the barrier, and which behaves in several respects as the Josephson current might be expected to.'

This was the first experimental verification of the existence of an effect discovered by means of an unusual piece of apparatus—a fountain pen. For the vacuum layer Anderson and Rowell substituted a layer of oxide, which was incomparably simpler to prepare. Painstaking checking indicated that the effect discovered experimentally was the Josephson effect. The magnetic field acted as arbiter in the debate. Investigating the dependence of the current in the barrier on the applied magnetic field by means of the apparatus of quantum mechanics, Josephson concluded that it should resemble the dependence of the intensity of Fraunhofer lines on their distance from the centre of the picture. Experiments in the dependence indicated that he was quite right; the similarity of the curve with the picture of the lines of Fraunhofer diffraction through an aperture that repeated the shape of the silhouette of the barrier once more demonstrated the quantum-mechanical character of the effect, which showed in tangible form on conventional instruments like ammeters and voltmeters.

10—1656

So the first of Josephson's effects was verified. And the time came for his second effect also to be confirmed.

We have already said that Josephson had really discovered two effects, although the second was a consequence and logical continuation of the first. In the first the barrier remained superconducting, i.e. there was no voltage in it. But what happened if a voltage V were applied to it? Then a pair of electrons crossing from the one superconductor to the other should have their energy increased by $2eV$, where e is the electron charge. But the exchange of electron pairs between two superconductors is a superconducting exchange, and the energy of the pair should not alter. Therefore a pair crossing from one superconductor to the other must get rid of this newly acquired energy, which it does by radiating photons, i.e. quanta of high-frequency electromagnetic radiation. The frequency of the radiation can be expressed by the formula

$$\omega = \frac{2\,eV}{\hbar}$$

where e is the electron charge and $\hbar$ is Planck's constant.

A high-frequency electromagnetic field is one with an alternating current. Consequently, by applying a constant potential difference to the Josephson barrier, we obtain an alternating current in the barrier circuit of very high frequency, whore effect in the external space should be detectable by the electromagnetic radiation emitted by the barrier, the existence of which had been postulated by Josephson.

Verifying of the existence of this second effect proved immeasurably more difficult than proving the first, primarily because the power of this radiation was extremely small and the waves were in a very awkward wave band, about which physicists still knew little. Because of that another way was taken, mainly involving organ pipes,

or rather the principle on which they work. An organ pipe is built for a certain, definite frequency, the same frequency that Bach and Buxtehude had in mind when they wrote a particular note on the staff. It also has the interesting property of echoing its frequency (or resonating) wherever that frequency is generated. So it singles out a weak signal of its frequency and transforms it into a strong and beautiful sound.

Exactly the same thing happens if the pipe is vibrated by frequencies that are multiples of the fundamental, i.e. by what are called overtones.

It was precisely this effect that the scientists used. They decided to apply electromagnetic vibrations from an external source to the Josephson barrier. The apparatus was made in such a way that the radiation frequency could be altered. At certain frequencies a sharp increase in the current was observed in the circuit. And when these frequencies were measured it was found that they corresponded exactly to the formula above, offering beautiful but indirect proof of Josephson's second effect.

Several members of the Ukrainian Academy of Sciences, I. Janson, V. Svistunov, and I. Dmitrenko, and the American scientists Scalapino, Taylor, and Eck decided to try for direct proof. They applied a waveguide to the barrier, using a metal pipe of rectangular cross-section in which an electromagnetic wave could be propagated practically without damping. The other end of the waveguide was attached to a supersensitive wave detector, so sensitive that it was capable of measuring the electromagnetic power entering the human eye from a hundred candlepower electric lamp situated 500 kilometres away from the observer. The apparatus did its job, and the existence of the second Josephson effect was firmly established.

The physicist A. Mieckewicz (better known under the pen-name of A. Dneprov) once predicted that all physical effects would eventually find practical application. The

area in which the Josephson effects could be used is now quite clear, and it is one of surprising beauty.

The Josephson effect is a very rare and unique physical phenomenon. In it quantum-mechanical effects, that are invisible and unsensed because of their ephemeral smallness, make themselves felt in our human, macroscopic world. Such a success is seldom the lot of a scientist. By simultaneously measuring the voltage and frequency of the radiation in the barrier, it is possible to measure the universal physical constant *e/h* with a degree of accuracy hitherto undreamt. The charge of an electron—just one!—and Planck's constant, which are needed at every step in physics will be measured by means of the most conventional earthly apparatus.

Fantastic possibilities are opened up for superaccurate measurement of magnetic fields by means of Josephson barriers. Each step in the volt-ampere characteristic of the barrier owes its occurrence to a change amounting to one quantum of flux in the magnetic flux passing across the barrier. It is almost inconceivable! To count the number of quanta in flux! For a quantum of flux is minute, only 2.07×10^{-7} maxwell (for comparison, the flux in a classroom horseshoe magnet is measured in hundreds of thousands of maxwells). Here, as before, quantum phenomena can be measured with ordinary laboratory apparatus. Magnetic fields of millionths of a gauss have already been measured by means of Josephson barriers.

In this way the Josephson effects, themselves a product of theoretical physics, will serve for the further development of the theories of quantum mechanics, especially those concerned with superconductive states.

They may possibly also find application in engineering. The unusually high sensitivity of Josephson barriers to a magnetic field and the relatively strong output signal have given scientists the idea of using them in the logic element for electronic digital computers. In a field of 0.5

gauss the conventional barrier, tin-oxide-tin, gives a signal output up to one microvolt, which even breaks the record set by the famous cryotron. To switch a cryotron requires a field of between 5 and 50 gauss, while its output voltage is only one-tenth that in the Josephson barrier.

Another very attractive possibility is that of utilizing the second Josephson effect to generate electromagnetic waves in the millimetre band. Unfortunately this part of the electromagnetic spectrum, with waves varying in length from a centimetre to hundredths of a millimetre, is comparatively little used in science and engineering because obtaining them is a vastly difficult and expensive business. The Josephson barrier presents a cheap, convenient, and straightforward source of low-power coherent radiation (i.e. all the waves in the same phase) and monochromatic radiation (all the waves of equal length) in the millimetre band.

There is, finally, another, at present still fantastic, possibility. The sensation that stirred the world several years ago never took place. The superconductors, predicted by Little—long organic molecules retaining their superconductivity even at several hundred degrees Celsius—for a number of reasons proved impracticable. At the International Conference on Low-Temperature Physics held in Moscow in September 1966 Little himself stated that, thanks to the help of Soviet colleagues, he had found a mistake in his calculations. The idea of a long, superconducting, organic molecule, however, closed in on itself and possessing surprising properties, was correct. The question that remained was how to use it. For it would have no ends, being closed in on itself. Who would need this superconducting 'thing in itself'? And what could we do with it?

There was silence in the hall until a young Soviet D.Sc., I. Dzyaloshinsky, rose and asked, half jokingly: 'Well, perhaps ... the Josephson effect?'

In which we learn how much scientific authority costs and make a trip to the Dutch laboratory where the phenomenon of superconductivity was discovered, where hopes faded and gave way to despair, but were revived again.

Back in 1913 Kamerlingh Onnes decided to build a superconducting electromagnet of 100 kilogauss that would not require any energy. He reasoned that since the resistance in a superconductor is zero, the current in a superconducting ring would circulate forever without fading. As we know, any current induces a magnetic field. So why not use a superconducting coil to make a powerful electromagnet that would not require a power supply? It would be a veritable revolution in electrical engineering and would save humanity millions of kilowatts at present futilely expended not only in the coils of magnets but also in the windings of electrical machines and transformers. And it would be possible to transmit electricity along superconducting lines without loss of energy.

Unfortunately Kamerlingh Onnes' dream of a superconducting solenoid of 100 kilogauss could not be realized, at least not in his lifetime. As soon as he attempted to pass a significant current along the superconductor, its superconductivity disappeared. Soon after it was discovered that a weak magnetic field, no higher than a few hundred gauss, also destroyed superconductivity. Since such small fields could be obtained more easily with permanent magnets, no one then was seriously concerned with building a superconducting magnet. And so the position remained for some twenty years.

Hopes of building powerful superconducting magnets were revived in the early Thirties when the Dutch physicists De Haas and Vuugd, Onnes's successors at Leyden (Onnes had died in 1926 and so did not live to see the practical application of his discovery), established that an alloy of lead and bismuth retained its superconductivity in fields in excess of 15 kilogauss. That at least made it possible to build superconducting magnets with fields up to that intensity. But no one did. The eminent physicist, W.H. Keesom, who was also working at Leyden laboratory, declared that the maximum currents at which a magnetic field cut off superconductivity in an alloy of lead and bismuth were insignificant. Sentence had been passed.

Possibly the most dramatic event in the history of superconducting magnets then occurred. It later emerged that Keesom had done something he had no right to do; he had extrapolated data obtained in weak fields into the realm of powerful fields. Unfortunately he had too much authority and standing. As soon as physicists heard about his results they gave up the idea of building superconducting magnets and turned to other things. It is now, however, known that the critical current for an alloy of lead and bismuth in fields up to 20 kilogauss is high enough to permit the building of high-field and extremely economic superconducting magnets. Keesom's authority cost physics very dear: the construction of superconducting magnets was set back another thirty years.

In 1961 Kunzler and his colleagues in the Bell Telephone laboratory announced that a bit of wire made of an alloy of tin and niobium—Nb_3Sn—remained superconductive in a field of 88 kilogauss even when a current of 1000 amperes per square millimetre passed along it.

Despite all its sensational nature this discovery was hardly a bolt from the blue for theoretical physics, since the Soviet physicist, A.A. Abrikosov, had already, in 1957, predicted the existence of high critical fields for compounds of this type. (It is worth mentioning here that Abrikosov, L.P. Gorkov, and V.L. Ginsburg were awarded the Lenin Prize in 1966 for their work on the theory of superconduc-

ting alloys and the properties of superconductors in high magnetic fields.)

The properties of the newly discovered superconductors made plans for utilizing superconductors in engineering more realistic. Superconductivity was given a new lease of life, as it were, and was now no longer a laboratory novelty but a phenomenon opening up very considerable perspectives for engineering practice.

The Strange Cold World of Superconductors

Which first gives a brief description of some superconducting materials and then recalls a quite strange, and at the same time unpleasant, phenomenon that rather marred the pleasure of the 'second birth' of superconductors.

If everything has gone so successfully, you may well ask, why are mammoth conventional magnets still being used? Why have superconducting magnets not yet won their rightful place?

Well, in the first place, because superconductors with good properties are very capricious materials. In order to handle them scientists have had to find the answers to new technological problems and develop a new approach to the nature of superconductivity. A great many superconducting electrotechnical materials have already been developed that are suitable for electromagnets, including such alloys as niobium+zirconium and niobium+titanium. These alloys lend themselves well to machining, and it is comparatively easy to draw them out into wire. Cynics, of course, would say that the wire is extremely expensive, as it is still made by the scientists themselves. But superconducting wire is already being produced in factories, which will inevitably bring down the price.

The most promising superconducting materials, however, alloys of niobium and tin and vanadium and gallium, are extremely fragile (for example the alloy of vanadium and gallium is easily reduced to powder between the fingers). Such compounds must therefore be packed into flexible tubes or laid on a flexible lining. Yet such a complicated process is justified, if only because magnetic fields up to 170 kilogauss can be obtained with superconducting solenoids wound from steel strip bearing a layer of a niobium-tin alloy. Furthermore the magnet weighs only a score or so kilograms and requires hardly any power instead of the scores of tons and thousands of kilowatts needed by a non-superconducting magnet of the same strength.

Superconducting solenoids can function almost without power, since a current once generated in them does not fade. And the amount of energy expended in the helium liquefier and in maintaining the magnets at low temperatures bears no comparison with the huge amounts used in non-superconducting magnets.

Naturally the building of superconducting magnets is not an easy business. One of the worst and unexpected difficulties designers encounter is the problem of the 'degradation' of the superconducting wire in the solenoid.

In order to understand what degradation is let us look, for example, at how the load a beam will support is determined. It is not necessary of course always to make tests. It is sufficient to know the material from which the beam is made and the character of the load being applied. The strength of the material being known—from small samples—the problem is reduced to one of making simple calculations. Roughly speaking, the ratio of the load a beam will support is directly proportional to the ratio of the cross-section and the maximum load of the sample. In other words whatever the length or the thickness of the beam its properties can be calculated in advance with more

or less certainty so long as we know the properties of a small sample of the same material.

But for superconducting alloys there are no such simple dependencies. If the cross-section of a wire is ten times greater than that of another wire made of the same material that in no way means that a current ten times as big can be passed along it. Moreover, the characteristics of a superconductor wire measured in a small bit do not coincide with those of long bits wound into a coil. Coils calculated for one field will actually produce another, significantly lower field.

This phenomenon is now explained by the magnetic field penetrating the superconductor as quanta of flux. Because the penetration is spasmodic and any change of the field in time induces emf, eddy currents are set up in certain sections of the wire that heat it and prematurely return it to the normal state. It is therefore necessary to increase the volume and weight of the coil in comparison to what would have been the case had the characteristics of short and long bits of wire been the same. That is a great disadvantage, especially on economic grounds, as superconducting wire is still not very cheap (about 1000 roubles a kilogram).

The problem of degradation is now being intensively studied. Occasionally they manage to compensate degradation. It can be reduced, for example, by coating the superconducting wire with copper; and it has been found that by increasing the thickness of the copper layer the properties of superconducting solenoids are significantly improved. So some researchers have concluded that the best material for superconducting magnets is copper into which a superconductor has been pressed. In such 'stabilized' systems the effect of degradation is totally absent.

Strangely enough another problem, which had been considered one of the more insurmountable ones, in fact proved comparatively simple to solve. In hitherto known

compounds superconductivity existed only at temperatures very close to absolute zero. No known superconductor can maintain its superconducting state at a temperature higher than 23°K (the transition temperature of a niobium-germanium alloy). And the forecasts of theoretical physicists were not very encouraging. They had established that, given the known mechanism of superconductivity, it was impossible in principle to obtain a substance that would remain superconducting at temperatures higher than 40°K, i.e. —233°C.

Helium, which liquefies at 4.2°K, is used to obtain low temperatures. Since even the slightest amount of heat penetrating the vessel containing liquid helium can cause it to evaporate rapidly liquid helium must be stored in special vessels with extremely efficient heat insulation.

The designers of superconducting magnets did not in fact have to solve the problem. They were able to make use of the results obtained by the people working on space research. The advances made by Soviet and American engineers working on the storing of rocket fuel in cryostats led to a reliable design and effective means of insulating these vessels, in which liquid helium can be stored for several months.

In addition, the problem of building a superconducting magnet whose field will persist at room temperature can also be considered solved (how it was done is shown in Fig. 35).

Victory over degradation and solution of the technical problem of maintaining superconductors at superlow temperatures have enabled scientists to create unique superconducting magnetic systems for research into plasma and for the magnetohydrodynamic installations of bubble chambers. In the USA for example a superconducting magnet has been built that induces a field of 40 kilogauss in a cylindrical volume 20 centimetres in diameter and 1.5 metres long. And a field of 70 kilogauss for a bubble chamber

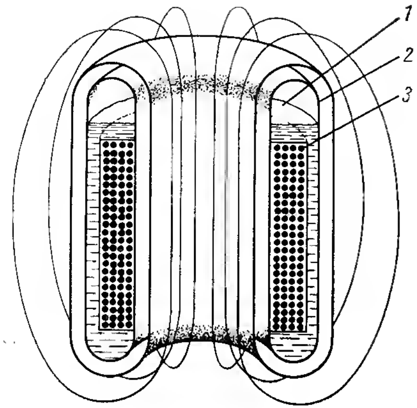

Fig. 35. The magnetic field of a superconducting coil at the temperature of liquid helium can also be used at room temperature if the Dewar flask holding the helium is tubular; *1*—liquid helium; *2*—evacuated cavity; *3*—superconducting coils.

has been obtained in a superconducting magnet with a diameter of 18 centimetres. Superconducting magnetic systems with fields around 20 kilogauss and a working diameter up to five metres have been built and tested. Thus the superconducting magnet of the bubble chamber at the Argonne National Laboratory in the United States has a magnetic field of 20 kilogauss and coils three metres high, weighing 45 tons, with an inner diameter of 4.8 metres and an outer diameter of 5.3 metres; four hundred kilograms of their weight comes from a superconducting Nb-Ti alloy and the rest from 'stabilized' copper. A brilliant success of superconductor technology was the building, in 1973, at the Kurchatov Institute of Atomic Energy, of a 'hybrid' magnet with a field around 250 kilogauss and a working volume three centimetres in diameter. In this 'hybrid' the field of a superconducting magnet is superimposed on that of an 'ordinary', water-cooled copper solenoid. American scientists have also reported the building of a 'hybrid' magnet with a field of 195 kilogauss.

CAUTION! Theoretically Impossible Equipment at Work

In which, without attempting in any way to convince the reader of the existence of a *perpetuum mobile*, we cannot resist the temptation of saying a few words about 'impossible' apparatus, and after quoting from *Gulliver's Travels* we describe a working d-c transformer that many patent experts had thought, until recently, could not exist.

In exploring the new, cold world of superconductors scientists had to look again at a host of problems they thought had already been solved. For example, what source of current is suitable to feed a superconducting system? When we are concerned with comparatively small currents then conventional batteries, generators, and accumulators would do in principle. But a current up to 1000 amperes can be passed along a superconductor with a cross-section of one square millimetre, and that is more than 100 times stronger than the current that can be passed along a copper wire with the same cross-section. This colossal advantage of superconductors gave engineers a new headache. For these thousand amps had to be obtained from a generator working at room temperature, and then transmitted along wires to the cryostat of liquid helium housing the superconducting magnet. The cross-section of the wires carrying the current (not being superconducting) had to be at least 100 times bigger than that of the superconductor, and (according to Fourier's Law) such a large cross-section would cause heat from the room to pour into the cryostat as if the floodgates had been

thrown wide open, so that the helium would boil away instantly and the superconductivity would be lost.

Therefore the designers had to devise apparatus that would generate these high currents not outside the cryostat but inside it. They managed it by utilizing the various special properties of superconductors, for example their diamagnetism. Diamagnetism is the explanation for the experiment of the 'suspended magnet' sometimes demonstrated in physics laboratories. Normally description of 'suspended magnets' usually abound in books on low-temperature physics; and they are also to be met in other books.

'I walked awhile among the rocks; the sky was perfectly clear, and the sun so hot that I was forced to turn my face from it; when all of a sudden it became obscured, as I thought, in a manner very different from what happens by the interposition of a cloud. I turned back, and perceived a vast opaque body between me and the sun, moving forwards towards the island... As it approached nearer over the place where I was, it appeared to be a firm substance, the bottom flat, smooth, and shining very bright from the reflection of the sea below.'

What Lemuel Gulliver, 'at the start a surgeon and later a captain of several ships', had seen was a flying island. At its centre a magnet had been set up on diamond supports, which, being repelled by some substance deep in the Earth, created lift.

Swift could hardly have foretold that two hundred years later the Moscow physicist V.K. Arkadyev would realize this 'mad' idea in almost exactly the same form, though on quite another scale. In his experiment a small magnet hung suspended, without any means of support whatsoever, above a lead plate. The experiment, sometimes called 'Mahomet's coffin' (according to legend, the coffin bearing the body of the Prophet Mahomet was suspended in space without support of any kind), was carried out at a temperature very close to absolute zero at which lead becomes superconducting.

The experiment is very important to us because it demonstrates the ideal diamagnetism of certain superconductors. The lines of force of a magnetic field cannot penetrate a diamagnetic body; and a diamagnet is an insurmountable barrier to them, an impenetrable wall or plane. But if that plane is not diamagnetic at even one point, it becomes a ring for the magnetic field, the same as the ring from which we obtain an electromagnet when we pass an electric current along it.

The difference between the magnetic properties of the superconducting and normal states of a conductor is so striking that it is quite possible to speak of there being two different materials. So it follows, in particular, for example, that a superconducting ring must not necessarily have a hole, i.e. an aperture in the conventional mechanical sense. A superconducting plate without an aperture can be considered, in the magnetic sense, as a ring if its superconductivity is destroyed at even one single spot not in contact with its edge.

A non-superconducting or 'normal' zone in a superconductor can be treated by various means: by heating it at some point to a temperature above the critical point, by applying a strong local magnetic field, or by illuminating a small area with a narrow beam of light (in the last case superconductivity is also lost through the dispersion of heat).

Using the fact that the location of the normal region (or 'aperture') on the surface of the superconductor is easily shifted, it is possible to create an accumulator of magnetic flux or, as it is sometimes called, a topological generator. Let us suppose that a superconducting plate has a real hole *1* in which a magnetic flux Φ_1 is set up and that in an area *2* the superconductivity is at the same time disturbed in some way without being mechanically destroyed. This non-superconducting region will act as a hole for the magnetic lines of force set up by the current flowing in the newly

formed ring. Now, if the location of hole *2* is shifted it is possible to create a situation in which the flux Φ_2 of the second hole will merge with the flux Φ_1 of the real hole which is the functioning area of a coil carrying a current. As a result the flux in hole *1* grows which is equivalent to an increase of the current in the coil surrounding it. In that way it is possible to obtain as large a current as required in a superconducting circuit without it coming into electric contact with the circuit that is at room temperature. The hole can be shifted by passing a sufficiently strong magnet over the surface of the superconducting plate. Through the action of its magnetic field, both the superconductivity and the diamagnetism will disappear and a hole will appear that will move together with the magnet. What is particularly notable about this design is that the direct current is taken from the stationary part of the apparatus. In essence it is a direct-current generator without a commutator, which has many times been demonstrated to be impossible in principle. Several dozen 'impossible' pieces of equipment are now working in Soviet, American, and Dutch laboratories.

It is not without interest that many eminent scientists have even said, on more than one occasion, that the idea of a d-c generator in which voltage would be taken from the stationary part of the machine is unrealizable. We must stress however, that their mistake was only that they were convinced that slipping brushes would be needed to pick up the current. The direct-current transformer is another of the machines considered impossible; and certainly, in a non-superconducting transformer a direct current cannot be obtained in the secondary winding. When a direct current is applied to the primary winding, a weak pulse current develops in the secondary winding but fades quickly because of the winding's electrical resistance.

But if the transformer has a superconducting secondary winding then, when a current is applied to the primary winding, emf is induced in the secondary creating a current that cannot fade even when the emf is no longer operating. With such d-c transformers with liquid helium a small current passed by fine conductors into a cryostat has been stepped up to 25 000 amperes.

So the special properties of superconductors are being used to overcome the difficulties arising from these same properties; and thanks to that approach generators and transformers have already been developed by which a superconducting magnet can be supplied with a current thousands of amperes strong. These immense currents circulate along the superconducting coils while a current of only a few amperes travels from the region at room temperature to the transformer or generator.

Such equipment also helps reduce the requirements of superconducting magnets for liquid helium, thus making them more economical.

What forecasts can we make at this stage about the future for superconducting magnets? The complete uncertainty on this question of a few years ago has given way to confident optimism. It looks as if in the not so distant future we shall have superconducting magnets with fields round 250 kilogauss and operational areas measured in metres. The magnets with such parameters will, of course, be many metres long, and weigh hundreds, or even thousands, of kilograms, and will require tens of kilowatts of power for their cooling systems. But, even though these figures are not inconsiderable, by comparison with non-superconducting magnets, we must remember, they are not so great, and are reckoned in metres not in kilometres, in kilowatts not in megawatts, in kilograms and not in tons.

Many people have been writing in recent years about the possibility of superconductivity being found in several linear polymers at room temperatures. Scientific opinion is divided on the feasibility such superconductors being synthesized. One thing, however, is clear: since it would

theoretically be possible then to obtain virtually any magnetic field, the opportunities for utilizing superconducting magnets would actually be infinite.

Where they might be employed is the subject of our next chapter.

Superconductors in Operation

A lengthy chapter in which we trace what has already been done with superconductors and what may yet be done.

Machines have penetrated all the forbidden corners of nature, it would seem; there are no unattained heights, and the bits of drilling rigs are boring into the bottom of the ocean. Man has tamed the terrors of pressure and the most rarified vacuum. There are installations in which he has created temperatures of millions of degrees; and the logic of events in technology is now leading to the first technical devices being lowered to the bottom of the temperature well, into the strange world of the lowest temperatures, as well as physical instruments that impassively register what happens there. And like any still unexplored world, the world of low temperatures conceals new enigmas and new treasures.

When, sixty years or so ago, superconductivity was discovered, the Dutch scientist Heike Kamerlingh Onnes, who did it, immediately realized that the golden age had dawned for electrical engineering. If we could eliminate the electrical resistance of conductors in the electromagnets of electrical machines, transformers, and transmission lines, current would flow in them without fading, and their properties would immediately become unique—their efficiency would be raised to nearly 1000.

Unfortunately, Kamerlingh Onnes's radiant dream of 'roses without thorns', of electrical engineering without

electrical resistance, was not to be. The very first research showed that a current of even the slightest significance could not circulate in the superconductors he had discovered (mercury, tin, and lead) without quenching their superconductivity. So the technical revolution he dreamed of did not come about, and the striking phenomenon of superconductivity passed, it seemed, into the limbo of student lab work as an intriguing physical curiosity, the embodiment, as it were, of perpetual motion; in many low-temperature laboratories around the world a current, albeit not very big, has circulated for years in superconducting lead rings immersed in liquid helium, without losing energy.

That rather dismal state of affairs was altered in the Fifties when the Soviet physicist A.A. Abrikosov showed the possibility in theory of there being superconductors with extremely favourable properties, such that they could be used with success in engineering. The widespread search for new superconductors that followed led to thrilling discoveries. A joyful gust of optimistic articles rustled the pages of scientific journals. New superconducting materials were discovered in many countries, and not now just metals but alloys as well that did not lose their superconducting properties even at very high currents and in strong magnetic fields. These materials proved mainly to be alloys of niobium and tin, zirconium, titanium, etc. Subsequent work led to the making of conductors, cables, and busbars from superconducting materials. Now technical application of superconductivity could begin.

The first d-c electrical machine with a superconducting field winding was built in the USSR in 1963. It consists of two parts: a low-temperature part cooled to 4.2°K (the boiling point of liquid helium) and a high-temperature part that is kept at room temperature. The low-temperature part consists of a cylindrical metal Dewar flask (41 mm in diameter) with double copper walls between which a high vacuum is maintained. The total thickness of the heat insula-

tion is five millimetres. Inside the Dewar flask is a short-circuited coil made of a niobium and tin alloy and immersed in liquid helium. The magnetic axis of the coil is perpendicular to the axis of the flask.

The superconducting coil for exciting this machine is made from an Nb_3Sn alloy and has four hundred turns. By means of a magnet that sets up a field of 20 000 oersteds a constant magnetic flux was 'frozen' into the coil as follows: the Dewar flask (without liquid helium) was put between the poles of the powerful electromagnet so that the axis of the coil coincided with the direction of the lines of force in the gap. In this way the coil was at the same temperature as the nitrogen jacket of the flask, i.e. 77°K, and was not superconducting (the critical temperature T_c for the Nb_3Sn alloy is 18°K). Then the helium (boiling point 4.2°K) was poured into the flask and the coil became superconducting. When the electromagnet was switched off, by Lenz's law a current was set up in the superconducting coil, that supported the constant magnetic flux connected with the coil. In that way the coil itself became electromagnetic. The magnetic flux in the coil short-circuited along the magnetic core intersects the wires of the winding of the rotating rotor. The voltage is drawn off from the rotor by means of conventional brushes.

Industry, and the power and electrical engineering industries in particular, could not let slip the broad opportunities being opened up by the application of superconducting materials. We may cite as an example the 2400-kW unipolar motor already built in Great Britain with a superconducting winding. In all respects (weight, size, cost, operating expenses, and reliability) this electric motor is superior to similar machines with copper field windings.

The outlook for superconductors as material for the windings in the very large electrical machines of big power stations (turbogenerators and hydroelectric generators) seems particularly exciting. The capacity of these machines is

growing year by year, but at the same time it becomes more and more difficult to build them. It is not a question of gigantomania but of the demands of the times; the greater the capacity of a single unit the lower is their unit cost of manufacture, the lower the volume of the civil engineering work on the power station, and the cheaper their operation; the faster is new generating capacity brought into operation, and the higher is the tempo of electrification.

Unfortunately, the possibilities of increasing the capacity of electrical machines are not unlimited. The 1200-megawatt generator with hydrogen and water cooling being built in the USSR is already close, it would seem, to the limit for machines of this type. Capacity is limited by many factors, namely: by the impossibility, with present cooling systems, of removing the great quantities of heat created by the electrical resistance of the windings; by the difficulties of making very large forgings; and even by 'railway dimensions', that is to say the limits imposed by railways (and road transport) on the dimensions of consignments.

If the field winding of an electrical machine (a field winding is, in fact, an electromagnet of special form) were made from a superconductor, that would immediately resolve a number of problems. First, the heating of the winding would cease. Second, the magnetic fields and currents in the machine would immediately increase several times over, which would lead to a marked reduction in its dimensions. Research already carried out indicates that a 2000-megawatt generator with a superconducting field winding would be much smaller than a 'conventional' one of a tenth that capacity. It is not surprising then that the development of superpowerful electric generators with superconductors is now one of the most important problems. Let us compare, for example, certain indices for hypothetical 'conventional' and 'superconductor' turbogenerators of 2000 megawatts capacity (taking the data for the 'conventional' one as 100).

	Turbogenerator	
	Of conventional design	With superconducting windings
Active length of stator	100	37
External diameter of stator core	100	97
Magnetomotive force	100	680
Overall length of rotor	100	50
Weight	100	30
Efficiency	100	100.5

How close are these plans to realization? What degree of reality can we attribute to such glowing prospects? Consider the progress that has already been achieved today in 'superconductor' turbogenerator technology.

In 1973 the Westinghouse Co. in the USA started testing a 5-MVA superconductor generator. Its field winding is housed in a cryostat filled with liquid helium and replenished from a 500-litre reservoir. The liquid helium cools the rotor winding through a specially developed assembly. The dimensions of the generator are close to those of a 'conventional' one. The designers hope to increase the power of their machine to 15 megavolt-amperes (15 MVA).

Thus the first steps towards superconductor generators have already been taken.

Great attention is now being paid in the USSR and other industrial powers to magnetohydrodynamic devices, the prototypes of very economic electric generators converting thermal energy directly into electricity.

The principle of MHD generators is well known; in accordance with Faraday's law of electromagnetic induction, an electromotive force arises in a conducting medium moving between the poles of a magnet. In MHD generators plasma at a temperature of 2000-3000 °K is used as the conducting medium. Since the temperature of steam in modern boilers and turbines does not exceed 700 °C and the efficiency of the conversion of thermal energy into electricity is greater the higher the temperature of the working body, it can be easily seen that the efficiency of MHD power stations would be significantly greater than that of conventional power stations. And the efficiency of a magnetohydrodynamic generator is theoretically as high as 70 per cent against the 40 per cent of the best conventional power stations.

But the efficiency of an MHD power station would in fact be considerably lower than that because the MHD generator itself consumes a certain amount of power to feed the magnet that maintains the magnetic field. It has been estimated that a coreless magnet or 25-MW MHD station would require 20 megawatts. The power needed by a magnet with a core would be lower but expenditure of materials would rise to 150 tons per megawatt against the one to five tons per megawatt of conventional turbogenerators.

The power needed by the electromagnet in a 500-MW MHD station would be approximately 60 megawatts. Such a large self-demand for energy is obviously impracticable and MHD generators will only be economic when they have superconducting magnetic systems.

To get an MHD generator of 200 megawatts capacity, a magnetic field of six teslas* would be required in a volume of 15 m × 5 m × 5 m. To obtain such an immense magnet by 'conventional' means, that is to say by means of copper windings, would call for a power consumption only a little less than the capacity of the generator. Only economic

* The tesla is the unit of magnetic induction, being the induction of a field such that each metre of conductor carrying a current of one ampere and lying perpendicular to the vector of induction is acted on by a force of one newton. It represents a flux of one weber per square metre. (See L. A. Sena. *Units of Pysical Quantities and Their Dimensions*. Mir Publishers, Moscow, 1972.)

superconducting magnets will enable this problem to be solved.

But is it really plausible to think of using superconductors, which normally function at 4.2°K, in equipment whose working parts are at 2500°K? In fact it is quite feasible, for modern types of insulation make it possible to separate 2500°K and 4.2°K by a wall only 1.5 to 2 centimetres thick.

We can visualize what the superconducting magnetic system for an MHD generator would look like. Two superconducting coils would be placed along the sides of the channel containing plasma, and the channel would be separated from them by multi-layer thermal insulation. The coils would be canned in titanium cassettes with titanium bars between them. The cassettes and bars should have to be extremely strong because the electrodynamic forces in the current-carrying coils would tend to break them and to attract them to one another. The forces would be quite large: in a field of 50 000 oersteds, for example, the elements would be under a pressure of 100 atmospheres.

As no heat is given off by a superconducting coil, the refrigerator needed by the superconducting magnetic system would only have to draw off the heat penetrating into the cryostat containing the liquid helium through the thermal insulation and the electrical leads. The losses due to the latter would be practically nil if short-circuited superconducting coils fed by a superconducting d-c transformer were used.

The helium liquefier making good the loss of helium boiled away by the heat influx through the insulation, should, it is estimated, provide five to ten litres of liquid helium an hour. Such liquefiers are produced by industry and occupy a space the size of an average room.

Several MHD generators with superconducting coils have been built, and others, albeit small ones, have been tested.

That is also the situation with thermonuclear power installations, which may possibly be successfully developed

in the not too distant future. The essential elements in such generators, for which ordinary water will be the fuel, will also be powerful superconducting magnets with fields of an intensity such as cannot be provided by conventional systems. The job is obviously insoluble unless superconducting materials are used.

Until very recently the conventional way of obtaining powerful fields by means of copper coils cooled by air, water, or oil was employed to make the 'magnetic bottles' and stabilizing coils for plasma research. But in large-scale experiments all these magnets have to be very bulky and consume much power. It has been calculated that the power needed to feed them would exceed the output of the thermonuclear generators and that at best a large, special power station would be needed to start up the generator.

Few doubt today that the only way to resolve this problem is to use superconducting coils. Then the power needed to maintain the magnetic field would be absurdly small, and power would only be needed to work the helium liquefier or refrigerator.

Equipment for thermonuclear research with a working area 20 centimetres in diameter and 120 centimetres long has already been built with a field at the centre of the solenoid of 300 000 oersteds. All the windings were made of a niobium-zirconium superconducting wire (25 per cent zirconium) 0.25 mm in diameter.

A mere 50 kilograms of superconducting wire were needed. The superconducting system works on the principle of a closed superconducting ring. Its initial feed comes from a rectifier employing power from normal a-c mains network.

So that damage to one coil should not destroy the whole system the system is divided into 24 parts, each fed separately. The current density in the superconducting coils reaches 400 amperes per square millimetre. The total weight of the system is 230 kilograms-force. It requires half a

12—1656

litre of liquid helium an hour. The liquefier to supply it is housed on a table.

Thus it is that the whole future of our power industry largely depends on the development of powerful superconducting magnetic systems. Happily, the outlook in this respect is very encouraging. The cost of superconductors, still very expensive, is falling steadily; experience of working with low-temperature equipment is piling up, and so too is experience of working directly with large superconducting magnetic systems.

We can assert with confidence that already, in the years ahead, superconducting systems, with a magnetic field of five or six teslas within a working volume of the order of several cubic metres will have been developed.

For more than half a century now there has been a steady flow of applications into the patent offices of various countries from inventors who want to patent proposals for transmitting power along cables working at low temperatures, including superconducting cables. But only recently, with the discovery of new superconducting materials, could this idea be given tangible form, and even now only in experimental set-ups. The first superconducting power lines are aluminium tubes coated with a thin layer of niobium alloy and carried inside pipelines through which liquid helium circulates. The helium pipeline, in turn, is inside another carrying liquid nitrogen, which serves as a kind of heat screen. In spite of the seeming complexity and cost of such a set-up, it is quite competitive with ordinary transmission lines, according to estimates that take into account the cost of the power lost in ordinary lines; and as superconducting materials become cheaper, superconducting lines will cost less than conventional ones.

We can already take it as proved that superconducting power lines with high transmission capacities will cost less than conventional ones. Research carried out in the USA into three-phase superconducting cables has been carried out on a pilot project with 38-mm niobium strands, rated at 1690 MVA at a voltage of 138 kilovolts and a current of 7.05 kiloamperes. The external diameter of the cable is 38 centimetres. The overall unit cost of building such a transmission line is 880 dollars per megavolt-ampere, which is approximately half the cost of a conventional cable system with the same parameters.

It is suggested that superconducting grids will be built along the following lines. A pipeline with liquid nitrogen will be laid in the ground between the end points. Inside this would be another pipeline with liquid helium carrying the superconducting line. The helium and nitrogen would flow along the pipelines because a pressure difference of several atmospheres would be created between the two end points. There therefore would only be liquefying and pumping stations at the ends of the line.

There would have to be electrical and thermal insulation between the conductors and the ground. The load on the helium refrigerator is significantly reduced by the use of liquid nitrogen in the pipeline, acting as thermal screening.

Another feasible form of thermal insulation would be a high vacuum surrounding numerous reflecting screens. But such a system would not ensure reliable electrical insulation while the electrical capacity of the numerous screens could be extremely large, which would be undesirable from the point both of transmission and of safety. And because of that the walls of the vacuum insulator would have to be of equal electric potential.

In the system with liquid nitrogen the nitrogen can be used simultaneously as a dielectric. Then insulated by the vacuum-screen device, the nitrogen pipeline would be below the potential of the earth and could contain nitrogen at a pressure of 12 to 15 atmospheres. The helium pipeline would also have vacuum insulation and would be supported inside the nitrogen pipeline by dielectric mailar or teflon posts (the dielectric properties of most insulators improve at

low temperatures). The helium pipeline in turn would be lined with a superconducting layer.

Taking into account the losses unavoidable at the ends of the line where the superconductor would come out onto the surface, it has been calculated that the total loss would be 1.2 per cent, which is a very low figure. Conventional transmission lines have losses of 1.5 to 2.0 per cent.

Finally we should note that power transmission employing superconductors at lower voltages and stronger currents presents special interest where overhead cables are ruled out (for example, in densely populated areas and with submarine power transmission).

It will probably become possible, also, by means of superconductors, to realize the most cherished dream of power engineers, that of storing large quantities of electricity. Electric power, we know, is an 'instant' product, if we can so express it. Power produced has to be consumed here and now, small accumulators do not come into it. But we still do not know how to store large amounts of power until they are needed. And so, in order to meet temporary maximum loads, power systems have to have huge, costly reserves of capacity that are drawn on only peak moments. If we could have 'power stores' it would not be necessary to build expensive reserve capacity; we could draw power from the 'store' as needed.

Here we may well recall the *perpetuum mobile*, the superconducting ring in which an electric current circulates indefinitely without loss of power. It is estimated that the peak loads of all the power grids of the European part of the USSR, for example, could be met by an enormous superconducting ring in which three thousand million kilowatt-hours of current were stored. The ring, with an inner diameter of 70 metres and a cross-section of 20 metres, would be a huge superconducting coil in the magnetic field of which power would be stored. The magnetic field would be so intense that the ring would have to be put in some

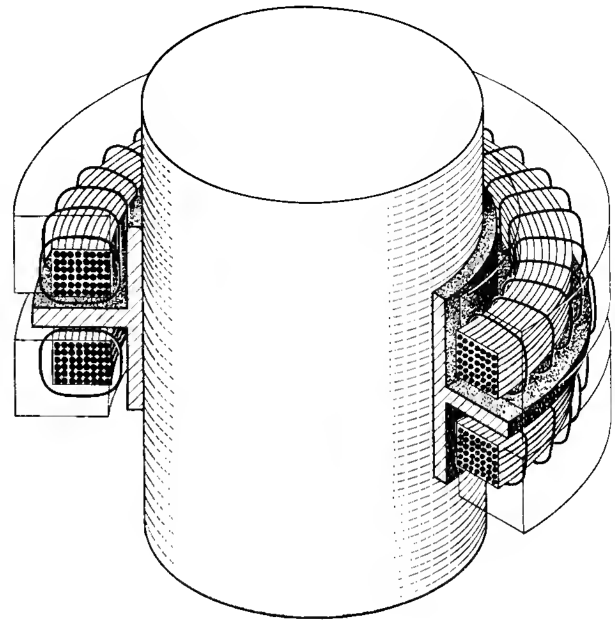

Fig. 36. The diamagnetism of superconductors can be used to make frictionless bearings in which the shaft does not touch the supports but is 'suspended' by the lines of force of the magnetic field.

sparsely inhabited locality, in order to avoid the harmful effects of the field on human beings.

All that, of course, is still fantasy. But the rapid development of superconducting technology is evidence, without doubt, that superconductors will soon occupy an honourable place in large-scale power engineering.

Quite new possibilities also exist now for the designers of low-power machines. The superconducting micromachines built so far are quite unlike conventional ones.

Because of the diamagnetism of a niobium disc the magnetic field set up in a coil made from superconducting wire can levitate the disc. Experiments indicate that one square centimetre of the 'hanging' surface can support a load of 300 grams. Quite big objects have already been lifted in this way. There is an account, for example, of a five-kilogram lead cylinder floating above the winding.

The 'magnetic mirror' principle can be used to make bearings which permit the shaft to float in a vacuum without contact with the support. Many models have already been built and tested.

The machines in a laboratory in America are of great interest. Not only do their bearings work on the 'magnetic mirror' principle but so does the electromagnetic interaction between stator and rotor.

If the rotor shaped like an empty tumbler is made from a superconductor and stood bottom uppermost with a magnet inside it, the tumbler 'surfaces' on the magnetic lines of force. If it is now put into the stator of a three-phase motor, the revolving magnetic field becomes the equivalent of two small magnets revolving around the surface of the stator on a single axis. Both the magnets repel the rotor and naturally there is no torque, since the direction of the force of repulsion passes through the tumbler's axis of rotation. If the glass is made hexagonal, for example, instead of round, there will be a torque that causes it to revolve at the velocity of the revolving field, since velocity increases as the frequency of the supply current rises.

A model working on this principle has been built in the USA; its speed of rotation reached 20 000 rpm and was only limited to that because the niobium glass (which weighed 26 grams) was then destroyed by the centrifugal forces. In this machine the rotating field is set up by sending pulses of direct current through the stator or by setting the voltages in two phases at a certain angle.

The disadvantage of such a design, however, is that it

is complicated to link it mechanically with equipment working at normal temperatures. A shaft connecting the motor (which operates at 4.2°K) with equipment operating at room temperature (300°K) would cause rapid boiling of the helium because of heat transfer. Therefore these machines still have only a limited field of application, namely, to drive low-temperature pumping equipment and precision superconducting gyroscopes.

A most difficult problem for physicists is separation of the isotopes of the different elements. Isotopes are atoms of the same element containing the same number of protons in their nuclei but having different numbers of neutrons. Consequently the masses of their nuclei differ, and so do their orbit when moving in a magnetic field; the trajectories of heavier nuclei are less distorted; therefore heavier nuclei move along different orbits than the lighter ones in a magnetic field. Even very similar isotopes can be divided in a powerful magnetic field but this method has not hitherto been widely used because huge magnets are needed to divide them effectively. Superconducting coils can literally revolutionize this branch of the atomic industry.

The possibility of superconducting magnets effecting a technical revolution in charged particle accelerators is also not excluded. The problem is that to get higher particle energies in accelerators, the latter must also be bigger and bigger. Modern synchrophasotrons weigh tens of thousands of tons and have diameters measured in hundreds of metres. Plans for accelerators of 500 to 1000 giga-electron volts envisage the building of magnets taking up an area between two and five kilometres in diameter. And of course such magnets will be incredibly expensive. It is very difficult to make them smaller because induction in a steel core of the magnets is limited by the saturation of steel and the diameter is in inverse proportion to the induction of the magnet. It has been calculated that, if it were possible to increase the intensity of its field from 16 000 oersteds

to 300 000, the gigantic accelerator at Berkeley could be stood on a dining table.

Their low energy requirement, lightness and small size make superconducting apparatus extremely convenient in space engineering. Indeed, since every joule of electricity, every gram of weight, and every metre of space must be taken into account, superconductors will be indispensable. On Earth it may be possible to sacrifice these characteristics for other considerations. The use of superconductors, for example, requires more sophisticated equipment, but in rockets, artificial satellites, and space vehicles that does not count: they cannot have apparatus that is large, heavy, or that consumes much power.

The American journal *Astronautics and Aeronautics* has described the valuable properties of superconducting systems for magnetic shielding against radiation. It is already possible to make large superconducting solenoids, and despite their high cost, arising basically from the cost of the superconductor (one kilogram of 75:25 niobium-zirconium alloy then cost 100 dollars), a superconducting screen has great advantages over those of other types because it is light and requires little power for cooling. In the cold of outer space (a few degrees above absolute zero) the need for refrigeration equipment is greatly reduced because the thermal influx from outside is very small. Only the influx from the walls of the cryostat heated by the Sun's rays will be large. And so as to avoid wasteful vaporization of the liquid helium in the cryostat space 'umbrellas' have been developed that reflect the Sun's rays and prevent the vehicle from overheating. The 'umbrellas' are made of laminated mylar coated with an aluminium film stretched on special frames and inflated with helium. The whole world followed with interest the installation of a huge defensive 'umbrella' on the American Skylab space laboratory.

In designing the magnetic defence system for space vehicles the concept of the Stormer radius was used. In physical terms it is the radius of the circular orbit of a particle in the equatorial plane of a solenoid. The idea was developed by the physicist F.C. Stormer during research into the aurora borealis. It difines the zone that is not penetrated by a charged particle of given energy. To protect a volume of 144 cubic metres effectively against protons with an energy less than one giga-electron volt by means of a Stromer radius of ten metres a 150-ton system would be needed which would include the weight of the supporting apparatus, the superconducting coil, and the cryogenic equipment.

More than nine-tenths of the weight of a magnetic screen is taken up by the weight of the supporting structure that prevents the solenoid being exploded by the very large electrodynamic forces (in a field of 500 oersteds the magnetic pressure is one atmosphere, but at 100 000 oersteds it is around 400 atmospheres).

Alternative screens, such as aluminium shields, are much heavier (more than three times as much) and have the drawback that when they are bombarded by high energy particles they can form secondary neutrons that add considerably to the resulting radiation behind the massive screen and the walls of the craft. And individual protection against radiation, in the shape of a double-layer diving suit with the space between the thicknesses filled with particle moderating drinking water, is less reliable.

The thrust developed by modern rocket engines is measured in thousands of tons. The big American Saturn-5 rocket used for moon shots has a thrust of 3 400 000 kilograms-force, which enables it to overcome the pull of the Earth's gravitational forces. When the rocket leaves the area effected by strong gravitational forces, however, such thrust is no longer necessary. Then, since the resistance of the medium is negligible the rocket can be accelerated by a much smaller thrust—a few grams only.

The first such small engines were employed on the Soviet Zond-2 interplanetary station. They are magnetohydrody-

namic in action, and it is no accident that magnet is the first term in this description. Everything that we have said about superconducting solenoid systems for shielding against radiation applies to the magnets in MHD motors, which can only be powerful, light, and economic if they employ superconducting magnets.

The most important part in the automatic piloting system of a space vehicle is the gyroscope. In most cases it consists of a disc revolving rapidly about an axis. No matter how the position of the vehicle alters in space the direction of the gyroscope's axis remains unchanged; or rather its position would remain absolutely unchanged if there were no friction in the gyroscope. Friction leads to definite errors in the vehicle's course; therefore the constructors had to concentrate on reducing friction in the gyroscope's supports. By using a magnetic pillow based on the ideal diamagnetic properties of superconductors they found it possible to reduce friction significantly and increase accuracy.

With magnetic suspension there is only friction between the revolving part of the gyroscope and the gaseous helium always present in the cryostat.

The first superconducting gyroscopes have already been built and tested, and they have proved to be freer of friction than any other type of gyroscope.

A major problem in building superconducting gyroscopes is the need for careful machining of the rotating sphere; any defect in its surface will seize the magnetic flux and cause zero to drift.

Another interesting possibility is that of using superconducting magnetic systems in the braking equipment of space vehicles.

The weight (or more exactly, the mass) of interplanetary stations could be significantly reduced if friction could be used, on entering a planet's atmosphere, to reduce speed. If a vehicle enters the atmosphere without braking it becomes heated due to friction and to the heating of the atmosphere in the jump of density around its head; and the greater its speed the hotter it gets. This heating could be reduced by means of magnetohydrodynamic equipment, but it is only efficient when the temperature of the gases is very high, as happens when the vehicle is travelling at high speed and the electrical conductivity of the plasma behind the jump in the condensation becomes so high that it can then be used as the working body of the MHD apparatus. If a magnetic field is applied to this plasma both it and the vehicle will be braked relative to each other without coming into contact, with the magnetic forces rather than the nose cone offering resistance to the flow.

By selecting the degree of the interaction between plasma and magnetic field it is possible to eliminate flow completely from the body so that its pressure and heat transfer to the body completely disappear. In such conditions braking forces will only develop in the coil creating the magnetic field. And since the area in which it is possible to create a magnetic field is quite large the effective braking section of the body is much increased.

So, by using this type of magnetic aerodynamics, more effective braking can be achieved without the vehicle itself becoming overheated. It is also useful that braking could begin in the more rarified layers of the atmosphere.

Even though entry into the atmosphere lasts only a few minutes, the value of using superconductors for braking is obvious, since the source needed to sustain the magnetic field even for this short period of time adds considerably to the weight of the vehicle. Furthermore the power needs of superconducting coils are several times lower than those of normal coils.

The number of processes both on Earth and in outer space that require instantaneous power is growing all the time. Such power can only be obtained by gradual accumulation. Today, condenser batteries are usually used or dynamite. Dynamite, however, can only be used when mechanical

power is required for a short period of time; in all other instances condenser batteries are used. But when considerable amounts of power are involved the batteries are very large so that, where weight is a decisive factor, they cannot be used.

Research has shown that the most suitable substitutes for condenser are coreless inductive coils. Large amounts of energy can also be stored in them; and while the density of the accumulated energy in a battery of condensers is 0.4 megajoules per cubic millimetres one hundred times as much can be accumulated in inductive coils and their superiority increases with the growth of stored capacity.

A basic problem when storing energy in a magnetic field is the loss of energy through the electrical resistance of the coils. If one million joules were stored in a field of 100 000 oersteds in a water-cooled copper coil the heat loss would be 1000 kilowatts and that, clearly, is not a sensible proposition.

It becomes much more economic to store energy in a magnetic field when superconducting coils are used. The absence of electrical resistance in the coils means that they can be slowly charged from a small power source, while there will be no losses through the Joule heating. It is possible to build a superconducting short circuit that stores energy for an infinite period of time. Superconducting magnetic stores of energy with a capacity of 2000 joules and a discharge rate of 0.001 second have already been tested.

The largest superconducting magnet in the world is three metres high, has an internal diameter of 30 centimetres and a magnetic field of 40 000 oersteds. Its power losses are incomparably less than in non-superconducting magnets with the same parameters.

Comparing the weight of such systems storing one million joules (the weight of the coil is determined in the main by the weight of the elements preventing it from breaking down) with the corresponding parameters for dynamite (0.24 kgf

per million joules), a curious fact emerges; the explosive power of dynamite is only ten times greater than that of a magnetic store. But the energy stored in the magnetic field is incomparably more convenient; it can be converted into electricity at any moment and then into light, mechanical force, thermal energy, etc.; and, moreover, it is possible to control the rate at which it is liberated.

All these properties ensure that magnetic energy stores will be widely used, especially for feeding the pulse lamps that fire masers. The prospects for using them in space are particularly attractive for there the vacuum can be utilized for thermal insulation and, with appropriate screening, low temperatures can be maintained by low-powered refrigeration.

The fact that superconducting energy stores have large currents at small voltages is also a great advantage in space, since most of the energy converters in space vehicles also have small voltages. The energy source can be joined directly to the store.

The apparatus discussed above do not, of course, exhaust the possibilities of superconductors in space. There are schemes, for example, for docking vehicles in space by means of superconducting magnets, for space 'workshops' where metals will be worked by means of superconductors, and for building electrical distribution circuits on the Moon consisting wholly of superconducting elements. But we must add that all these projects are still only in their preliminary stages.

They are all still only dreams but reality gives them a solid basis. A few years ago scientists found the key to the most important problem, that of the magnet. And the key was superconductivity. And it may yet open up new, even more fantastic possibilities; then everything we have only been dreaming about in this chapter will be ordinary entries in the record of the progress achieved by means of superconductivity.

Obtaining, Storing, and Transporting Liquid Helium

A chapter that explains itself.

We have been talking about how superconductivity, which promises such a brilliant future for the technology of high magnetic fields, can exist only at temperatures close to absolute zero. Liquid helium is usually used to obtain these low temperatures because it is the only substance that does not solidify in the temperature interval between 1°K and 10°K.

The best method so far of cooling gaseous helium and obtaining it in liquid form was devised by P.L. Kapitza in 1934 and involves a detander, a compressed-gas driven engine. Essentially what happens is that the helium gas is expanded in a special vessel, pushing a piston and therefore, in doing work, giving off energy. So the helium cools. By repeating the process many times it is possible, in principle, to cool the helium down to 4.2°K at which it liquefies. But the process is generally combined with other methods of cooling such as throttling.

In throttling, helium that has already been compressed and cooled is passed through a narrow slit or throttle, in which it expands. The physics of cooling by throttling (the Joule-Thomson effect) is that the gas increases in volume when it expands in the throttle and the intermolecular distances in it increase and thus work is done against the forces of attraction. So the gas loses internal energy and consequently cools.

One of the best modern helium expansion liquefiers, the G-3, was built at the Institute of Physical Problems of the USSR Academy of Sciences. It works on the following principles.

A piston compressor compresses helium coming from gasholders and forces it into the liquefier, at a rate of 350 cubic metres an hour at 22 or 23 atmospheres. Initially

the helium is cooled in a bath of liquid nitrogen (70°K). Then some of the cooled gas is passed into a detander where it expands, driving the piston; there its temperature drops to 11 or 12°K. This cold helium is now used to cool fresh amounts of helium. Another part of the cooled gas passes to the throttling stage where it is forced through the throttle, which causes it to cool even further; about 10 per cent of the original quantity of helium is liquefied.

The apparatus produces 45 litres an hour, consuming 2.5 kilowatt-hours of electricity per litre of cooled helium. This efficiency is not the limit. Apparatus has been built more recently in the USA that produces 200 litres of liquid helium or more an hour. Is that high or low productivity?

The heat of evaporation of liquid helium is rather low (4.8 kilocalories per kilogram); a four-watt electric lamp burning in liquid helium would vapourize more than 50 litres in an hour.

Nevertheless, the total absence of resistance in superconducting coils and, consequently, the fact that no heat is liberated mean that such quantities of liquid helium are quite enough even for the largest coils. It is only necessary to ensure excellent thermal insulation around the superconducting coil to prevent influx of heat from outside.

The best insulation is a good vacuum (with a residual pressure of 10^{-5} to 10^{-6} mm Hg). Then the thermal conductivity of the residual gas is too low for there to be any noticeable heat transfer. With vacuum insulation heat transfer through radiation is of decisive importance. In order to eliminate, or at least substantially to reduce, heat transfer from the high-temperature region to the low-temperature one through radiation, reflecting screens cooled by some cooling agent have to be put in the vacuum. The screens must be cooled because radiant heat transfer is proportional to the difference of forth powers of the surface temperatures. Therefore reducing this difference can have a big effect on the thermal insulation. Suffice it to say that a screen cooled

by liquid nitrogen cuts the flow of heat into the low-temperature region by 200 times.

Liquid helium is kept in special Dewar flasks, which are normally spherical since a sphere has the smallest surface area for a given volume and every superfluous square centimetre of surface represents extra heat flow. The vessel most commonly used in the USSR holds about ten litres of liquid helium. The helium is contained in a spherical reservoir inside a nitrogen bath, which in its turn is kept inside a spherical holder that is at room temperature. A high vacuum is created in the space between the outer holder and the vessels containing nitrogen and helium; the loss of helium is less than 2 per cent a day.

There are larger standard vessels holding, for instance, 50, 80 or 100 litres, and the development of superconducting technology may lead to much larger capacities. In the USA helium cisterns holding 10 000 to 30 000 litres are already used to provide a centralized supply of helium. In these gigantic installations rather different principles of thermal insulation are employed. So-called multi-screen vacuum insulation is used, that is to say the vacuum gap filled with as many as 100 layers of aluminium foil separated by insulating materials like glass cloth or glass paper.

The problem of transporting liquid helium through pipes, which especially concerns those working on developing superconducting power lines, is to all intents and purposes solved. The principle on which these pipes or cryostats are built is practically the same as that of Dewar flasks. An inner pipe containing liquid helium is surrounded by concentric nitrogen screens, which are placed in turn in an outer casing at normal temperature. The inside of the helium pipe is coated with a superconducting film which is the conductor for this still exotic power line.

The first experiments in developing large cryogenic systems have brought reassuring results. We are sure that we shall soon witness surprising new progress in this field.